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Research Article

Study on the Coalbed Methane Development under High In Situ Stress, Large Buried Depth, and Low Permeability Reservoir in the Libi Block, Qinshui Basin, China

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Coalbed methane (CBM) has been exploited in the deep area of the coal reservoir (>1000 m). The production of CBM vertical wells is low because of the high in situ stress, large buried depth, and low permeability of the coal reservoir. In this paper, efficient and advanced CBM development technology has been applied in the Libi Block of the Qinshui Basin. According to the characteristics of the coal reservoir in the Libi Block, the coiled tubing fracturing technology has been implemented in four cluster horizontal wells. Staged fracturing of horizontal wells can link more natural fracture networks. It could also expand the pressure drop range and control area of the single well. This fracturing technology has achieved good economic results in the Libi Block, with the maximum production of a single horizontal well being 25313 m^3/d and the average single well production having increased by more than 60% from 5000 m^3/d to 8000 m^3/d. Based on the data regarding the bottom hole pressure, water production, and gas production, the production curves of four wells, namely, Z5P-01L, Z5P-02L, Z5P-03L, and Z5P-04L, were investigated. Furthermore, a production system with slow and stable depressurization was obtained. The bottom hole pressure drops too fast, which results in decreasing permeability and productivity. In this work, a special jet pump and an intelligent remote production control system for the CBM wells were developed; hence, a CBM production technology suitable for the Libi Block was established. The maximum release for the CBM well productivity was obtained, thus providing theoretical and technical support for CBM development with geological and engineering challenges.

1. Introduction

Coalbed methane (CBM) is an unconventional natural gas generated by geological and biological processes in coal seams [1, 2]. Being a type of clean and efficient energy with wide applications, the development and utilization of CBM has attracted increasing attention in many countries around the world, including China, the United States, Russia, Canada, and Australia [3]. China is rich in CBM resources, particularly owing to a huge amount of large buried depth resources, which accounts for over 61.9% of the total resources [4]. In the deep buried reservoirs of 1500–3000 m, the proven CBM reserves of CBM reached 30.37×10^{12} m^3 [5, 6]. Due to the complicated geological conditions and low degree of CBM resource exploration, the CBM development technology needs to undergo a deep innovation process.

CBM development in China began in the early 1990s. Currently, thanks to the introduction of advanced CBM development technologies [7], China has made great progress in CBM exploration and development. Since CBM is mostly concentrated in the coal seams of medium and high-rank coals, these coal seams suffer different degrees of damage, which determines the strong heterogeneity of the CBM reservoir. The typical characteristics of CBM reservoirs are low pressure, low permeability, low saturation, and high in situ stress [8]. Due to the general characteristics of three low and one high coal reservoirs, many difficulties still exist in the theory and technology of large-scale CBM development in China [9]. The well production is mainly dependent on hydraulic fracturing and CBM production technology. Hydraulic fracturing is the most widely used system of stimulation in CBM technology. Many studies have shown that the production of CBM can be significantly increased by hydraulic fracturing of coal reservoirs [10, 11].

CBM hydraulic fracturing stimulation and optimization of production technology are the most effective means to improve the coal reservoir seepage channel and to increase production. Previous research studies have examined that hydraulic fracturing can be used to improve coal seam permeability both in China and abroad [12–14]. Hydraulic fracturing technology is one tool to provide effective paths for the seepage of gas and to increase the productivity of reservoirs [15]. Laboratory studies on hydraulic fracturing are useful to understand the fracturing treatment as field conditions are complex [16–20]. Optimizing the hydraulic fracturing technology is an important step to improve CBM production [21]. Over 90% of CBM wells are improved by hydraulic fracturing in the United States [22]. The mechanism of hydraulic fractures in coal seams is of great significance for designing an optimal hydraulic fracturing process.

The production of CBM consists of a series of processes, namely, depressurization, desorption, diffusion, and seepage. CBM mainly exists in the coal matrix in the adsorption state, and it is necessary to reduce the reservoir pressure through drainage to develop CBM [23, 24]. Being different from conventional reservoirs, coal seams are characterized by high stress sensitivity and strong anisotropy. In order to solve these technical problems, researchers have conducted extensive studies on the optimization of CBM production [25]. In CBM well production processes, it is easy to cause pulverized coal blockage damage, stress sensitive damage, and gas/water lock damage. The principle of CBM production is to reduce the bottom hole pressure through drainage and then reduce the fluid pressure in the reservoir [26]. As a result, the adsorbed CBM is desorbed due to depressurization, which provides the adequate conditions for CBM production. According to the exploration and development of CBM technologies in the south of the Qinshui Basin, it is found that large-scale gas production generally occurs only when the bottom hole pressure is lower than the critical desorption pressure. In CBM production process, it is necessary to establish a reasonable production pressure difference (the pressure difference between the bottom hole pressure and the reservoir pressure) and control the production rate of pulverized coal [27].

According to the classification standard of the original permeability of coal seams, the permeability of the No. 3 coal seam in the Zhengzhuang-Libi Block belongs to a low-medium permeability range. This work focused on the high in situ stress, large buried depth, and low permeability in the Zhengzhuang region of the Libi Block, offering a semi-quantitative description of the productivity features of the CBM wells using coiled tubing driven fracturing technology and an intelligent production management system. Considering the poor development of vertical wells under complicated geological conditions, this paper favored an efficient and advanced CBM development technology suitable for the Libi Block.

2. Location and Geological Conditions of the Libi Block

The Zhengzhuang region is located in the south of the Qinshui Basin, Shanxi Province, and the Libi Block is situated in the west of Zhengzhuang region, as shown in Figure 1. The terrain of this block is mainly hilly and mountainous, with an altitude varying from 600 m to 1000 m. The No. 3 coal seam of the Shanxi Formation in the Libi Block shows a monoclinal structure. Due to the squeezing effect, the local structure in the block exhibits an interphase structure with high north-south and low middle. The stratigraphic structure is relatively simple, with only seven faults with small fault distance being developed. The resource conditions of the No. 3 coal seam are as follows:

(1) The buried depth of the coal ranges between 500 m and 1150 m, while the developed coal seam is buried at a depth of 600–900 m

(2) The coal is mainly composed of a primary structure and of a cataclastic structure to a lower extent; the fracture connectivity is medium

(3) The coal seam thickness is between 3.53 m and 6.74 m, with an average of 5.45 m; the coal gas content is relatively high, the majority existing within the range of 18–21 m^3/t

(4) The average porosity of the coal is 3.66%; the coal permeability is low, with the original permeability being 0.1–0.4 mD.

According to the mechanical tests performed on the coal seam, with its roof and floor rock, in the south of the Qinshui Basin [28], the No. 3 coal seam is characterized by low strength, low elastic modulus, and high Poisson's ratio compared with the rock. The coal is prone to deformation and failure under the action of in situ stress [29]. Table 1 shows the mechanical parameters of the No. 3 coal seam, alongside with its roof and floor.

3. Influence of In Situ Stress on Hydraulic Fracturing Fractures

The hydraulic fracturing technology can improve the seepage channel and thus enhance the permeability of the coal reservoir, providing the most effective means to improve the production of the CBM well. The results of hydraulic fracturing mostly depend on geological conditions and engineering parameters. Different degrees of horizontal stress are likely to induce different hydraulic fracture networks [30]. In addition, the natural fractures in reservoirs can affect the performance of hydraulic fracturing [31]. Since coal reservoirs in China are generally characterized by low pressure, low permeability, low gas saturation, and strong heterogeneity, hydraulic fracturing stimulations are required in order to provide guidance for CBM exploration.

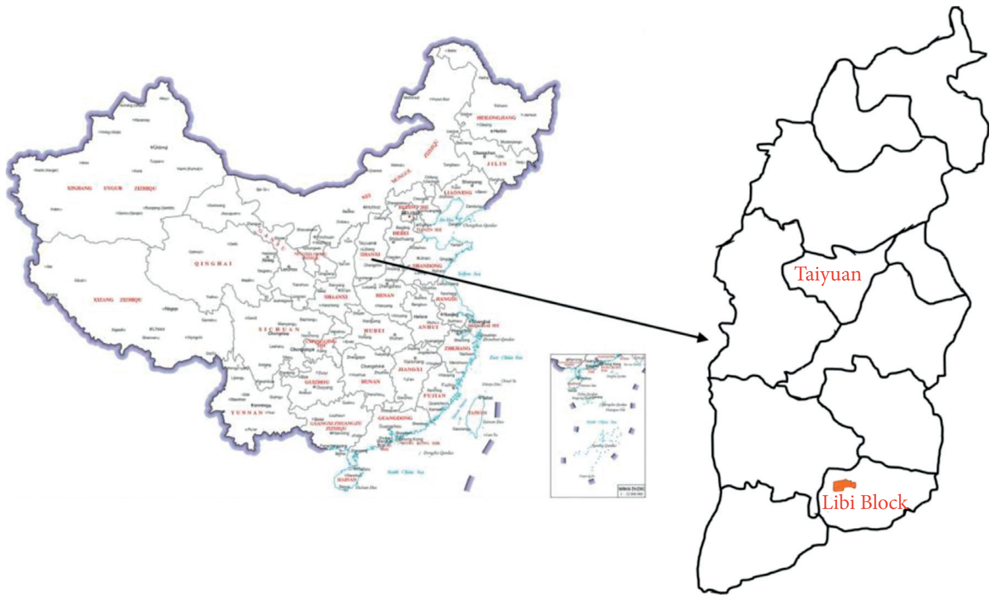

Figure 1: Schematic diagram illustrating the Libi Block location.

Table 1: Mechanical parameters of the coal seam in the southern Qinshui basin, alongside with its roof and floor [28].

Stratum	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)	Poisson's ratio	Rock softening coefficient
Roof of the No. 3 coal seam: mudstone and sandy mudstone	31.45–39.28 36.10	1.39–1.78 1.61	0.28–3.25 2.29	0.26–0.31 0.28	0.33–0.63 0.48
No.3 coal seam	2.51–20.91 11.10	0.09–0.93 0.48	0.21–1.63 0.91	0.28–0.33 0.31	0.22–0.58 0.46
Floor of the No.3 coal seam: argillaceous siltstone	20.39–36.05 27.92	0.90–1.63 1.24	0.63–3.01 1.97	0.27–0.31 0.29	0.23–0.55 0.42

The data representation is provided as (Min – Max)/mean.

Compared with shallow coal reservoirs, deep coal reservoirs have higher in situ stress and formation temperature [32]. The in situ stress state changes with the buried depth, and its coupling with the formation temperature determines the different mechanical properties of deep coal reservoirs. Furthermore, the in situ stress affects the permeability and stimulation effect of deep coal reservoirs. The relationship between in situ stress and formation fluid pressure determines the effective stress of deep coal reservoirs, thus affecting the seepage capacity in the production process [33]. In view of the complex geological conditions of high in situ stress, large buried depth, and low permeability, horizontal well channels must be established through hydraulic fracturing to change the fracture closure caused by in situ stress [34, 35].

In situ stress, also known as original rock stress, is the naturally existing stress in the stratum which is not disturbed by engineering. In situ stress includes vertical stress, minimum horizontal stress, and maximum horizontal stress. Vertical stress is induced by the weight of the overlying formations. The minimum horizontal stress is the main factor that enables the control of the hydraulic fracture propagation. Hence, the minimum horizontal stress is the key parameter for reservoir stimulation design. In situ stress in this region can be accurately estimated via the following empirical equations [5, 36–39]:

$$\sigma_V = 0.027\,D, \tag{1}$$

$$p_p = 0.0122\,D - 2.8886, \tag{2}$$

$$\sigma_h = \frac{\nu}{1-\nu}\left(\sigma_V - p_p\right) + p_p + b\sigma_V, \tag{3}$$

$$\sigma_H = 0.0343\,D - 4.6618, \tag{4}$$

where σ_v is the vertical stress, MPa; D is the buried depth of the formation, $D > 300$ m; p_p is the pore pressure, MPa; σ_h is the minimum horizontal stress, MPa; ν is Poisson's ratio; b is minimum stress coefficient, $b = 0.035$; and σ_H is the maximum horizontal stress, MPa.

Horizontal well fracturing is an effective technology for complex geological conditions with high in situ stress and low permeability [40]. For the CBM reservoir in the Libi Block, hydraulic fracturing technology and refracturing technology with active water, large displacement, and medium sand ratio have been implemented [41, 42].

The fracture type produced during hydraulic fracturing in horizontal wells depends on the in situ stress condition [43]. Fractures formed by fracturing can be divided into four types: transverse fractures, longitudinal fractures, oblique fractures, and twisted fractures [44]. It is widely accepted that coal permeability reduces exponentially upon increasing the effective stress [45]. At shallow depths, vertical wells without hydraulic fracturing can obtain a reasonable depletion area, owing to the high permeability of the coal seam. However, in deep regions, horizontal wells with the stimulation method have to be applied to enhance gas production [46].

Horizontal wells produce crisscross fracture networks during hydraulic fracturing. The propagation law for longitudinal fractures produced by hydraulic fracturing is similar to that of transverse fractures. However, due to the limited coal reservoir thickness, the propagation range of longitudinal fractures is smaller than that of transverse fractures under identical fracturing conditions [47]. As the fracture network range increases, the range of the coal reservoir stress increases, and the fractured reservoir area becomes larger, which improves the desorption range of the coal reservoir.

With the development of CBM gradually permitting the extension of reservoirs to depths below 1000 m, the domestic and foreign CBM fracturing stimulation technology has the following characteristics:

(1) Hydraulic fracturing of a single vertical well is developed to the staged fracturing of horizontal wells
(2) Based on the active water, multifracturing fluid gradually becomes favored
(3) The single primary fracturing develops to the deplugging fracturing and re-fracturing
(4) The scale of fracturing increases, and the trend towards fracturing factory is observed

4. Coiled Tubing Driven Fracturing Technology

With the development of unconventional oil and gas such as shale gas, tight gas, and tight oil, staged fracturing of horizontal wells has gradually developed into an important engineering technology. More attention has been focused on staged fracturing in horizontal wells of CBM, which has become an effective method to increase gas production. The number of fracturing sections in horizontal wells has increased from 5 to 10 in 2008 to more than 20 now. Since 2007, staged horizontal fracturing has been widely used in unconventional oil and gas developments in North America [48]. In 2011, staged fracturing was first performed in horizontal wells of CBM in China. After recent years of development, staged fracturing of horizontal wells of CBM has been carried out in the southern of the Qinshui Basin [49].

4.1. Introduction to Fracturing Technology. Staged hydraulic fracturing in horizontal CBM wells can improve the seepage conditions and form a complex fracture network of natural fractures, cleat joints, and artificial fractures. Hydraulic fracturing expands and extends the pressure drop funnel for CBM production, thus improving the single well production. The fracturing fractures of CBM wells generally extend along the direction of the maximum principal stress. In the case of the No. 3 coal seam in the Libi Block, the maximum principal stress direction is NE-SW, the fracture pressure gradient is 2.32–7.34 MPa/100 m, with an average of 3.98 MPa/100 m. The stress gradient is between 1.03 MPa/100 m and 3.15 MPa/100 m, with an average of 2.09 MPa/100 m.

The well layout area has the following characteristics. (1) Simple geological structure, no fault, and relatively small coal seam dip angle. (2) Complete structure, which favors overall deployment and coordinated depressurization. (3) A relatively flat terrain, which allows an easy construction of the cluster well site and reduces surface investment. (4) Orthogonality between the borehole trajectory of cluster horizontal wells and the direction of maximum principal stress, which improves the fracturing effect. (5) A moderate buried depth with good permeability. The surface layout of CBM well site is shown in Figure 2.

In the CBM development of the Libi Block, coiled tubing driven fracturing technology is used in cluster horizontal wells for hydraulic sand blasting perforation, which can be completed in a single operation. The fracturing technology in the Libi area will be implemented in accordance with the CBM industry standard "technical specification for CBM well fracturing." The proppant combination consists of 40–70 mesh, 16–30 mesh quartz sand, and 12–20 mesh low-temperature curable coated sand. The fracturing fluid is composed of clean water and 2% KCl. During the perforation process, coiled tubing is used for fluid injection with a displacement of 0.7 m^3/min and a sand ratio of 2–5%.

Hydraulic blasting perforation technology applies the Bernoulli principle: through the nozzle throttling, the high-pressure perforating fluid in the tubing is transformed into high-speed jet to shoot through the casing and reservoir rock. During operation, the quartz sand for perforation is mixed with perforating fluid in the sand mixer truck, pumped by the fracturing truck, and injected through coiled tubing, shot casing, and reservoir rock. The fracturing fluid is injected through the annulus of coiled tubing and casing, and the fracturing fluid is then injected into the reservoir through the hole opened by the casing. Subsequently, the proppant is pumped into the fracture. At the completion of the fracturing process, the coiled tubing packer is lifted up, and the next layer is positioned again. The packer is set again, and sandblasting perforation is carried out to complete the fracturing of all layers. A diagram of coiled tubing driven fracturing is shown in Figure 3.

The coiled tubing driven fracturing technology permits continuous fracturing operation through the processes of coiled tubing sandblasting perforation and back annulus sand fracturing, thus solving the problems of long fracturing cycle and high construction cost. Staged fracturing of horizontal wells can extend through more natural fractures, which is beneficial to stress release and reduces the damage to the reservoir caused by fracturing [50, 51]. The coal seam section of the four cluster horizontal wells in the Libi Block has a length of 804–812 m, which is divided into 7–9 stages of fracturing. The corresponding fracturing parameters are shown in Table 2.

(a) (b)

Figure 2: Surface layout of CBM well site.

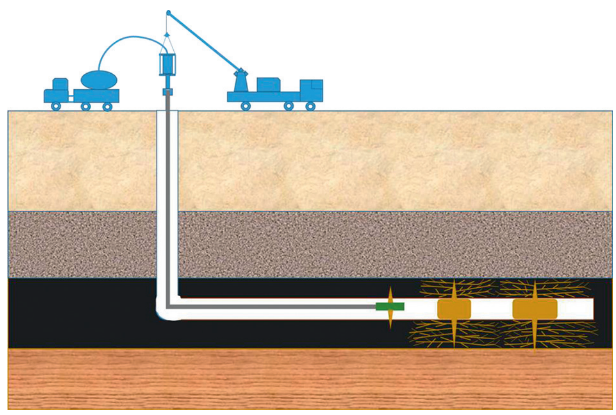

Figure 3: Schematic diagram of coiled tubing driven fracturing.

Table 2: Fracturing parameters of the four cluster horizontal wells in the Libi Block.

Well no.	Well depth (m)	Fracturing length (m)	KCl concentration (%)	Number of fractured sections	Fracturing interval (m)	Amount of sand added (m^3)	Fracturing fluid volume (m^3)
Z5P-01L	2082	809	2	7	85–135	272.30	7062
Z5P-02L	1891	806	2	7	85–131	267.87	6618
Z5P-03L	2020	812	3	9	87–114	225.9	7108
Z5P-04L	1850	804	5	8	96–129	295	3514

The application of coiled tubing staged fracturing technology in the Libi Block has achieved good results. The technology can monitor the bottom hole pressure in real time and permits remote monitoring of fracturing data. The fracturing operation is fast and efficient and can be put directly into production after fracturing. All horizontal wells that have been put into operation have achieved high and stable production. The Libi Block set a record for the highest gas production of a coal reservoir with high stress, large buried depth, and low permeability on July 31, 2015. The maximum production of a single horizontal well is 25313 m^3/d, and the average stable production of a single well is 8100 m^3/d. The average production of a single vertical well in the area around is less than 600 m^3/d.

5. Engineering Case: Libi Block Production Control Technology

Combined with the coal reservoir conditions in the Libi Block, the ideal pressure difference between the bottom hole pressure and the reservoir pressure is established for the production process. The horizontal well jet pump and intelligent remote control system have been developed to permit accurate control of pulverized coal production speed and ensure the CBM production. An intelligent drainage system with jet pump control technology as the core was established. This system integrates three functions: data acquisition, data transmission, and system control. Utilizing this system, the pressure drop can be controlled within

5 kPa, which permits an increase in the intelligence of drainage information collection, transmission, and control, thus allowing real-time remote control of CBM well production parameters.

5.1. Special Jet Pump for CBM Well. Almost all CBM production equipment is introduced from the oil industry. The problem of eccentric wear of pipe and rod occurs frequently in the CBM well production with the rod pump. Pulverized coal can cause problems related to pumps sticking, such problems reduce the production efficiency and increase the construction cost. In situations where characteristics of long drainage and gas recovery period, unstable water production, and difficult control of initial gas production pressure are found, CBM production control is gradually developing towards automation, intelligence, and refinement.

Due to the stress sensitivity of coal reservoirs and the fragility of coal, pulverized coal will be produced in the CBM production process. The retention of pulverized coal in fracturing fractures reduces their conductivity. This leads to premature productivity attenuation in CBM wells. The pump sticking problem caused by a large amount of pulverized coal production leads to frequent pump inspection, thus causing large fluctuations in the bottom hole pressure, destroying the continuity of gas production, and finally affecting the productivity of the wells. Therefore, pulverized coal control is an important component in CBM well production management.

The high-pressure power fluid provided by the ground pump is transformed into high-speed flow beam through the nozzle of jet pump, and a low-pressure area is formed at the suction inlet of the jet pump. The down hole fluid is drawn into the low-pressure zone and mixed with the power fluid. In the diffusion tube, the kinetic energy of the power fluid is transferred to the down hole fluid to increase its pressure and discharge to the surface. The jet pump gas recovery device will discharge the power fluid, containing both pulverized coal and formation sand, through the liquid return pipe, in order to avoid pump sticking. The jet pump has several advantages, including simple structure, high reliability, and ability to accurately record dynamic data such as the bottom hole pressure. The jet pump reduces the failure rate of the equipment, prolongs the workover cycle of the inspection pump, and improves the overall work efficiency. The working principle diagram of the jet pump is shown in Figure 4.

5.2. CBM Intelligent Production Management System. The production management system introduced in the Libi Block is an intelligent oil and gas well production control system. According to the mainstream production concept, this system attains automatic regulation of gas and water production of CBM wells through remote control of production terminals and feedback of production data. This system functions primarily consist of data acquisition, data transmission feedback, automatic control, and remote monitoring. The system schematic diagram is shown in Figure 5.

5.3. The Engineering Application. The CBM intelligent production management system has been used in the Libi Block since July 31, 2014, with well numbers Z5P-01L, Z5P-02L, Z5P-03L, and Z5P-04L. Among these, the Z5P-03L well has the highest production, with the maximum daily gas production reaching 25313 m^3/d. The system equipment is in good condition, which ensures the timely transmission of data from wells and the adjustment of anomalies in the block.

5.3.1. Production Data Analysis. Since wells Z5P-01L, Z5P-02L, and Z5P-03L were put into production, continuous production has been maintained and the formation gas supply has been sufficient. However, the production has room for improvement and more stable production capacity. The well Z5P-04L was seriously affected by the collapse of a column on the east side of the block, and its gas production was unstable. Table 3 shows the production data of horizontal wells in the Libi Block.

The gas production process of the CBM well consists in dropping pressure through drainage, and the CBM is gradually desorbed, migrated to the wellbore, and discharged to the surface [52]. Based on the theory of "desorption-diffusion-seepage" of CBM [53, 54] and the production data of the Libi Block, CBM production can be divided into four stages: drainage and pressure reduction stage, gas production increase stage, stable gas production stage, and productivity test stage. In this paper, three production data of bottom hole pressure, water production, and gas production were selected to optimize the production of four cluster horizontal wells, namely, Z5P-01L, Z5P-02L, Z5P-03L, and Z5P-04L in the Libi Block. The production curves of the four wells are shown in Figures 6–9.

5.3.2. Drainage and Pressure Drop Stage. The coal reservoir in the Libi Block is found in the unsaturated state, and the reservoir pressure is higher than the critical desorption pressure; thus, it is necessary to decrease pressure through drainage. During the stage of drainage and depressurization, if the drainage intensity is too high, the closure of coal seam fractures and cleats can be easily induced. Therefore, it is necessary to maintain a reasonable drainage intensity to ensure that the fracturing fractures remain open. When the bottom hole pressure drops below the critical desorption pressure, the coal seam begins to desorb gas, and the appearance of casing pressure is the marker for the end of this stage.

The drainage stage of well Z5P-01L lasted for 58 days, and the bottom hole pressure dropped from 8.718 MPa to 4.452 MPa, with an average pressure drop of 73.5 kPa/d. As can be seen in Figure 6, the maximum water production of well Z5P-01L was 34.6 m^3/d, and the average water production was 17.33 m^3/d, which is much higher than the stages of gas production increase and stable gas production. The drainage stage of well Z5P-02L was 110 days, with an average pressure drop of 43.8 kPa/d. Its maximum water production was 46.51 m^3/d, while the average water production was 26.09 m^3/d, thus larger than that of the other

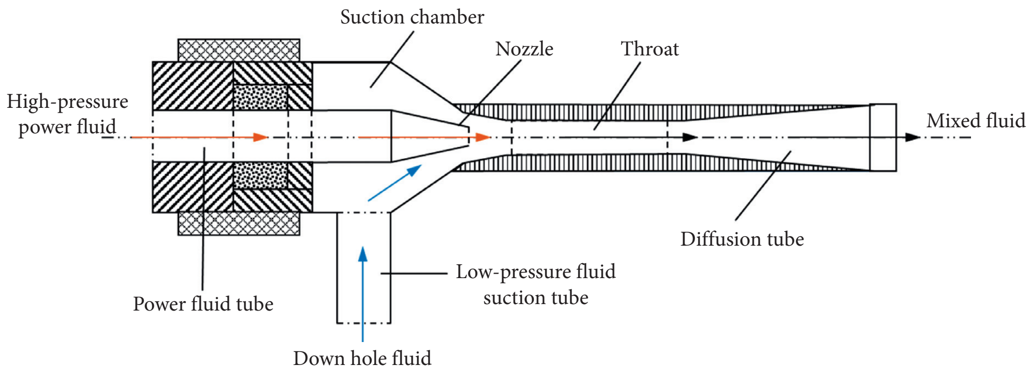

FIGURE 4: Working principle of the jet pump.

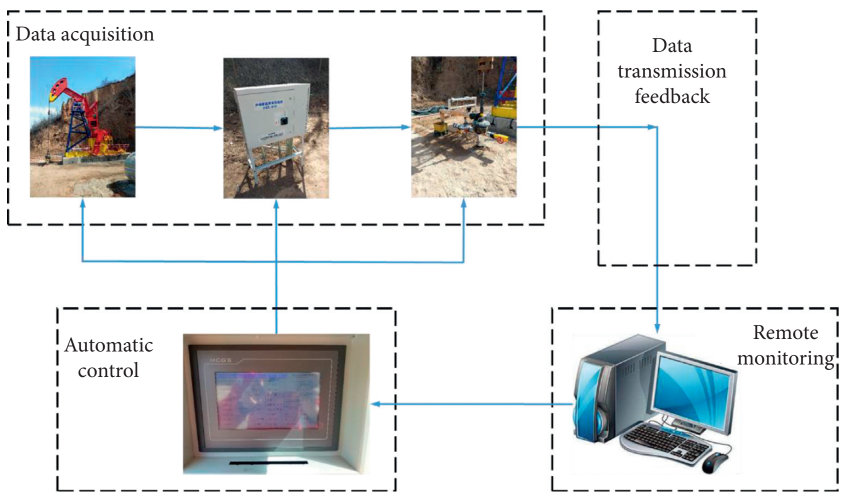

FIGURE 5: Schematic diagram of the intelligent production management system.

TABLE 3: Production data of horizontal wells in the Libi Block.

Well no.	Commissioning date	The date of production	Bottom hole pressure (MPa)	Casing pressure (MPa)	Daily gas production (m^3/d)	Cumulative gas production (10^4 m^3)	Cumulative water production (m^3)
Z5P-01L	2016/9/16	2017/8/19	0.808	0.655	14428	256.27	1498.8
Z5P-02L	2014/11/10	2017/8/19	0.177	0.096	4549.6	465.72	4267.2
Z5P-03L	2014/10/30	2017/8/19	0.048	0.048	7275.0	821.43	4133.2
Z5P-04L	2014/7/28	2017/8/3	0.375	0.038	3818.2	242.27	4189.7

three wells, as shown in Figure 7. The drainage stage of well Z5P-03L was 85 days with an average pressure drop of 57 kPa/d. As can be seen in Figure 8, the drainage time of well Z5P-03L was about 30 days shorter than that of Z5P-02L. The maximum water production and average water production in this stage were 46.13 m^3/d and 26.56 m^3/d, respectively. The drainage stage of well Z5P-04L was 85 days (not including the 31 days of shut down due to well Z5P-03L). The bottom hole pressure dropped from 8.447 MPa to 3.815 MPa, with an average pressure drop of 54.5 kPa/d. As can be seen in Figure 9, the maximum water production at this stage was 30.76 m^3/d, and the average water production was 21.24 m^3/d.

5.3.3. Gas Production Increase Stage. A small pressure drop range should be set at the beginning of the gas production increase stage. In this way, the desorption area near the wellbore zone can be enlarged, and the porosity and permeability of the coal reservoir can be increased. It is beneficial for the water flow at the far end to have enough time to link with the wellbore area, thus expanding the effective

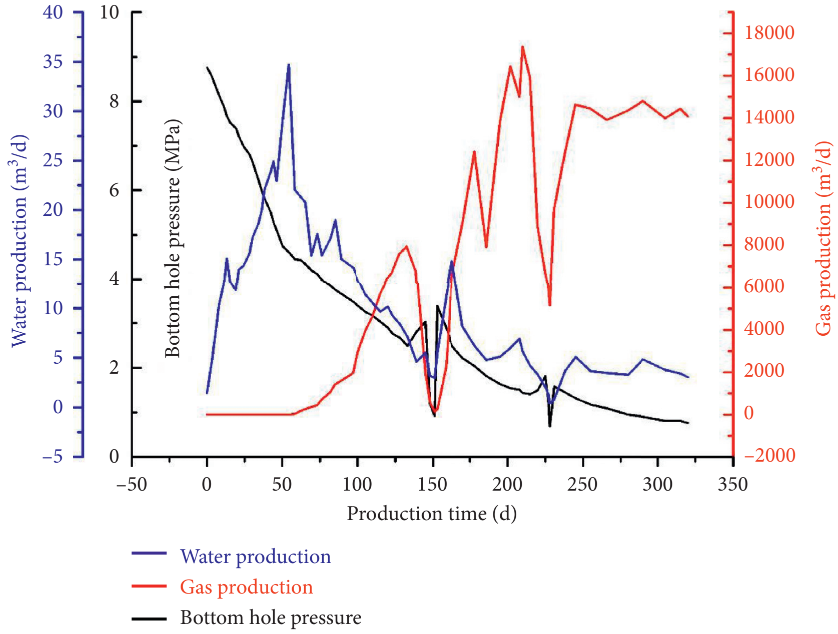

Figure 6: Production curve of well Z5P-01L.

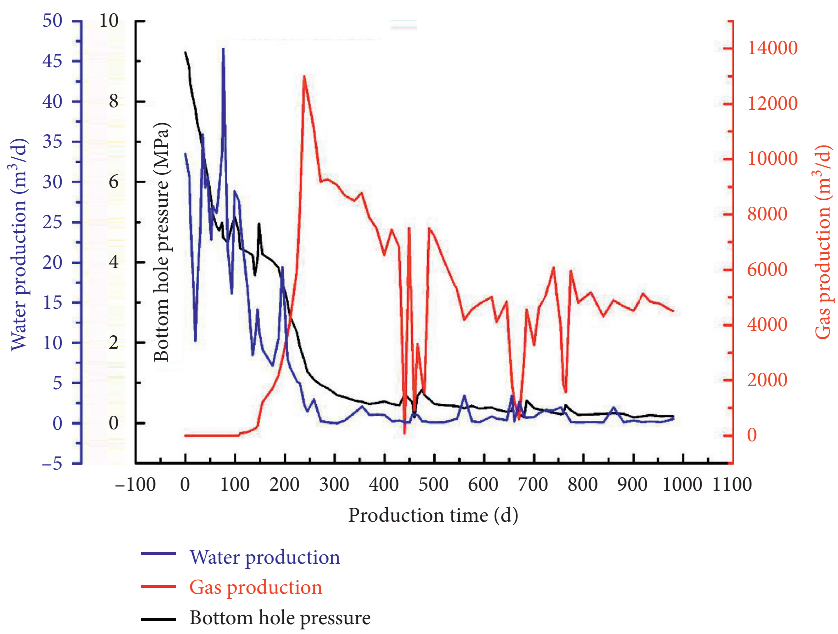

Figure 7: Production curve of well Z5P-02L.

control area of the wellbore. The gas production increase stage is related to the gas water two-phase flow. As the gas production increases, the relative permeability of the gas phase increases gradually. At the same time, the water production decreases and the relative permeability of the water phase decreases.

The casing pressure of well Z5P-01L was formed on November 13, 2016. Since then, the casing pressure increased rapidly, indicating that the coal reservoir started desorption. By January 29, 2017, the bottom hole pressure decreased from 4.491 MPa to 2.517 MPa, while the gas production increased from 0 to 8164 m^3/d. As the casing pressure appeared in well Z5P-02L, a pressure drop of 5 kPa/d was recorded, which corresponded to the bottom hole pressure dropping from 4.337 MPa to 3.886 MPa. At the same time, the gas production increased from 0 to 300–400 m^3/d. Due to the small increase rate in gas production, the pressure drop range was increased from May 15, 2015, to July 9, 2015. The bottom hole pressure dropped from 3.886 MPa to 1.443 MPa, and the gas production increased from 356 m^3/d to 12301 m^3/d.

The casing pressure of well Z5P-03L appeared on January 24, 2015, with a pressure drop of 5–10 kPa/d. During this period, the bottom hole pressure decreased from

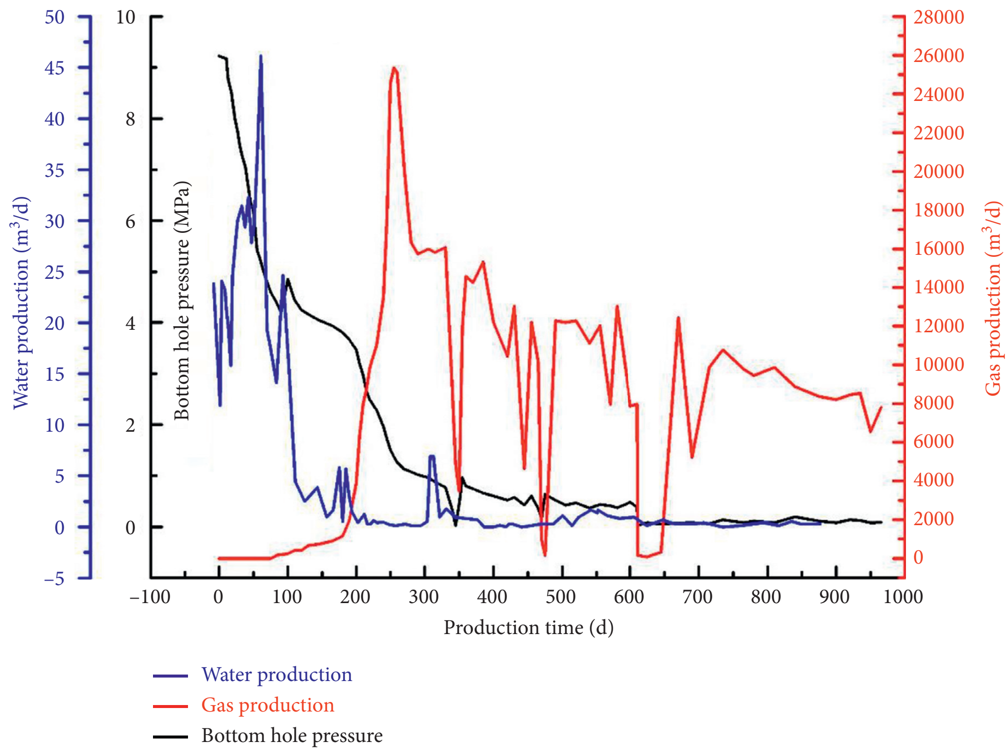

FIGURE 8: Production curve of well Z5P-03L.

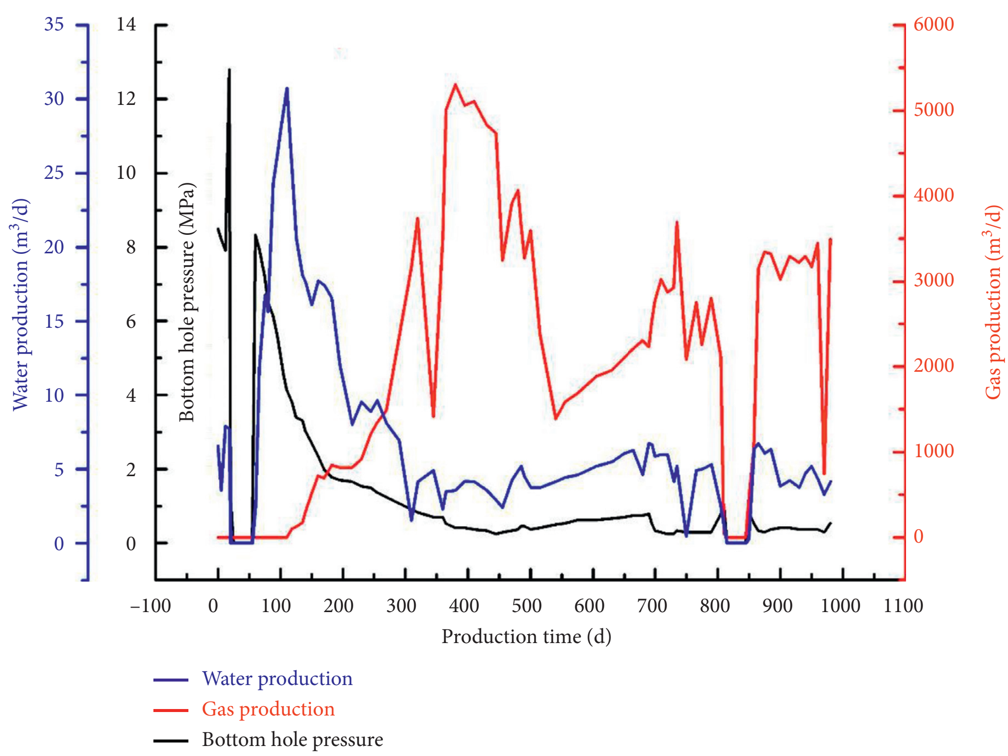

FIGURE 9: Production curve of well Z5P-04L.

4.352 MPa to 3.594 MPa, and the gas production increased from 0 to 2545 m^3/d, which was larger than the corresponding variation for well Z5P-02L. The gas production increased from 2545 m^3/d to 25137 m^3/d, while the average gas production increased by 396 m^3/d, thus with a rate of production nearly twice as fast as that of well Z5P-02L.

The initial pressure drop of well Z5P-04L was 50 kPa/d. The larger production pressure difference can cause the coal reservoir to produce gas earlier and increase production rapidly. The pressure drop lasted for 60 days, during which time the bottom hole pressure dropped from 3.815 MPa to 1.941 MPa, while the gas production increased from 0 to 854 m^3/d. Under rapid depressurization, the gas production rose at a small rate, thus not achieving the expected output. In the later stage, the pressure drop range was reduced to 10 kPa/d, which allowed the pressure drop funnel to expand outwardly, and the gas production increased to 3737 m^3/d after 150 days of drainage.

5.3.4. Stable Gas Production Stage. In this stage, the CBM well has formed a relatively stable pressure drop area, and the production parameters tend to be stable. It should be noted that, although the gas production in this stage has been stable, the decrease in water production is still expected to cause a decline in the gas production. At this stage, the bottom hole pressure drops fast, which is not conducive to the late recovery of CBM wells. The performance of the stable gas production stage directly determines the final cumulative production of CBM wells.

When the bottom hole pressure of well Z5P-01L drops to 1.518 MPa, the gas production reaches the peak value of 17373 m^3/d (see Figure 6). The cumulative stable production of well Z5P-02L lasted 11 days, and the gas production was more than 12000 m^3/d. Maintaining the production of 12000 m^3/d, the pressure drop range showed a gradual downward trend, indicating that the effective control area of the well was still in further expansion. The cumulative stable production of well Z5P-03L lasted 10 days, and the gas production was more than 25000 m^3/d, while the pressure was reduced from 1.519 MPa to 1.264 MPa. The gas production of well Z5P-04L was unstable and fluctuated greatly due to the influence of the column collapse and the multiple pump inspection operations, which did not favor the later development of the well. At present, the gas production is about 3800 m^3/d, which is far less than the other three wells (see Figure 9).

5.3.5. Productivity Test Stage. A reasonable production intensity is the key factor to achieve stable and efficient CBM wells. An excessive production intensity causes stress, water, and velocity sensitivity of the coal reservoir, which will damage the coal reservoir and hinder the later improvement of gas production. If the production intensity is too low, the drainage time is increased alongside with the development cost.

As shown in Table 4, wells Z5P-02L, Z5P-03L, and Z5P-04L were tested for productivity over a period of 40 days. Well Z5P-02L was tested for a stable production of 9000 m^3/d, during which time the maximum, minimum, and average daily gas production were 10587 m^3/d, 8823 m^3/d, and 9219 m^3/d, respectively. The productivity test of well Z5P-03L was conducted with a steady production of 16000 m^3/d. During the test, the maximum, minimum, and average daily gas production were 18298 m^3/d, 15646 m^3/d, and 16195 m^3/d, respectively. The productivity test of well Z5P-04L was conducted with a steady production of 5000 m^3/d. During the test period, the maximum, minimum, and average daily gas production were 5330 m^3/d, 4289 m^3/d, and 5023 m^3/d, respectively.

6. Discussion

6.1. Influence of Hydraulic Fracturing on CBM Production. The reservoir pressure is the energy source for fluid flow in coal reservoir; thus, the bottom hole pressure is the core of CBM drainage control. Through periodic drainage and depressurization, the bottom hole pressure drops below the critical desorption pressure, and CBM continuously desorbs from the coal matrix, migrates to the wellbore, and discharges to the surface.

Reservoir pressure and critical desorption pressure are the two main factors affecting CBM drainage and production, which can be described in terms of the critical reservoir ratio. The critical reservoir ratio is defined as the ratio of the critical desorption pressure to the reservoir pressure. Since most coal seams are under saturated, the critical reservoir ratio is generally less than one. Different critical reservoir ratios correspond to different desorption pressures. The larger the critical reservoir ratio is, the closer the desorption pressure is to the original formation pressure. Furthermore, a higher critical reservoir ratio corresponds to a shorter pressure drop time and a faster gas production. If the critical reservoir ratio is small, the difference between the desorption pressure and the original formation pressure is large, and gas desorption will occur after a long time of drainage and depressurization. Compared with the vertical well, the L-shaped horizontal well after hydraulic fracturing exhibits relatively higher critical reserve ratio and gas saturation.

Under the same geological conditions, the gas production of the cluster horizontal well is obviously higher than that of the single vertical well. After hydraulic fracturing, with the continuous discharge of formation water, the production pressure difference gradually increases and the desorption area of the coal reservoir becomes larger, thus improving the gas production potential of the cluster horizontal well. The use of L-shaped wells in the Libi Block has promoted the development of CBM.

In the production process, the large water production is a significant feature of the L-shaped horizontal well. Indeed, a large amount of fracturing fluid is injected during fracturing, which causes the natural and artificial fractures to connect, and the water in the reservoir increases. Furthermore, the drainage and pressure drop stage is the single-phase flow, and the relative permeability of the water phase is one. In this stage, the range of depressurization is large, and the water is produced in a larger amount. As the gas begins to desorb, the relative permeability of the water phase decreases gradually, which causes the water production to decrease gradually, thus entering the gas water two-phase flow stage. Upon increasing the gas production, the relative permeability of the gas phase increases gradually, while the water production further decreases.

6.2. Influence of Production Intensity on CBM Production. In the CBM well production process, the production intensity is the most important factor affecting the well

Table 4: Gas production data in the productivity test stage.

Well no.	Total test time (d)	Maximum daily gas production (m^3/d)	Minimum daily gas production (m^3/d)	Average daily gas production (m^3/d)	Target gas production (m^3/d)
Z5P-02L	40	10587	8823	9219	9000
Z5P-03L	40	18298	15646	16195	16000
Z5P-04L	40	5330	4289	5023	5000

productivity. Low production intensity results in long drainage time, high investment cost, and poor economic benefit. Excessive production intensity leads to the closure of fractures in coal seams, which renders the gas unable to transit from the adsorption state to the free state, thus affecting the final productivity of the CBM well. Therefore, in order to improve the final productivity, drainage and pressure drop must be performed according to scientific standards. By analyzing the geological conditions, hydraulic fracturing effects, and CBM well production historical data, different production intensities should be applied to different pressure drop stages.

(1) In the initial drainage stage, the lower displacement keeps the bottom hole pressure stable, which lasts for about 10 days.

(2) After entering the drainage and pressure drop stage, the bottom hole is in the state of the single-phase flow. After hydraulic fracturing, the fracturing fluid needs to be discharged at a higher speed, thus the pressure drop rate is faster in the early stage of production. According to the buried depth of the coal seam, a drop in the range between 50 kPa/d and 200 kPa/d is enforced, and the range is reduced as the cumulative bottom hole flow pressure drops by 1-2 MPa. The bottom hole pressure is continuously reduced until it decreases below the critical desorption pressure.

(3) As the coal reservoir begins to desorb, it enters the stage of pressure drop and gas production increase. When the casing pressure appears, the pressure drop range should be controlled within 500 kPa/d, and stable gas production should be adopted after imposing a cumulative decrease in the bottom hole pressure of 1-2 MPa. The pulverized coal should be discharged stably to establish a good channel for gas production. At the same time, the bottom hole pressure should be reduced slowly over a long period of time to prevent the reservoir fracture from closing due to the excessive production pressure difference. The duration of this stage mainly depends on production rate, productivity requirements, and reservoir response.

(4) In the stable gas production stage, when the gas production reaches the target value, the productivity test is conducted for about 40 days. The stability of the bottom hole pressure and water production must be strictly controlled during the test.

Figure 10: Jet pump core diagram.

6.3. Influence of Production Equipment on CBM Production. The normal operation of the production equipment is an important guarantee for continuous production. The CBM production equipment is composed of surface and underground parts [55]. The surface pump continues to provide power for the down hole unit. The surface instrument collects production data in real time and transmits them to the control cabinet, thus ensuring that the production has the data support. The down hole jet pump has a long service cycle, which prolongs the pump inspection cycle and provides guarantee for continuous production. The core of jet pump is shown in Figure 10.

During the production process of the Libi Block, the intelligent production management system collects a large number of production data. The data are timely transmitted to the server to provide sufficient data support for dealing with abnormal production well conditions. Through the production curves of four horizontal wells, a production system of continuous depressurization, stable depressurization, and reasonable release productivity is obtained. During the production process, the output of pulverized coal is accurately controlled.

7. Conclusions

In this work, an effective way to develop CBM in high in situ stress, large burial depth, and low permeability reservoirs was investigated, and theoretical and technical support was provided for the efficient development of future CBM processes. Four cluster horizontal wells were put into production in the block. As of August 1, 2017, the bottom hole pressure of the four horizontal wells was between 0.432 MPa and 0.843 MPa, while the daily gas production was 32334 m^3/d, with an average of 8083.5 m^3/d. These four cluster horizontal wells adopted the coiled tubing staged fracturing technology to increase the CBM gas production per well by more than 60%, and the average single well production increased from 5000 m^3/d to 8000 m^3/d. The main conclusions of this study are as follows:

(1) The coiled tubing driven fracturing technology can accurately locate and carry out targeted fracturing operations according to the reservoir and in situ stress characteristics of each fracturing point. Through the optimization of operation parameters and fracture spacing, a wellbore fracture grid system was established to enable fracture communication between the wellbore and coal reservoir.

(2) The Libi Block implements a technology consisting of combining the gas production device of the jet pump with the intelligent remote production control system. This system can accurately control the bottom hole pressure. The fine management and control of the cluster horizontal wells was realized to ensure continuity and stability of production.

(3) According to the production data, the Libi Block production can be divided into four stages: drainage and pressure drop stage, gas production increase stage, stable gas production stage, and productivity test stage. By studying the production curves, a production system with slow and stable depressurization was obtained, thus enabling the realization of the maximum well productivity.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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