Study on the Mechanism of a Multi-branch Horizontal Well in Enhancing the Production Performance of Coal-Bed Methane Reservoirs in the SY Block, Qinshui Basin

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Abstract. In recent years, with the government's continuous attention to coalbed methane (CBM) exploration and development and the scholars' extensive research on CBM, China CBM industry has achieved rapid development. It has grown from an annual production of 0.3 billion cubic meters in 2005 to 4.96 billion cubic meters in 2017, forming two important CBM production bases in the Qinshui Basin and the eastern margin of the Ordos Basin. However, the rapid increase in annual CBM production mainly depended on the increase in the number of producing wells because of the low average gas production of CBM wells. There are many reasons to explain why the single well production is so low, but the principal one is that geological conditions of coal reservoirs are complex, such as low permeability, under-pressure, strong plasticity and so on. Besides, there is another important and crucial factor, affecting the production performance, that the exploitation technology is relatively simple and unsuitable for those geological conditions. This study takes the SY block located in the north of the Qinshui Basin as an example to analyze the production performance and technical advantages of a multi-lateral horizontal well as well as the production performance of the adjacent vertical wells. The results show that, for low permeability coal reservoirs, multi-lateral horizontal wells have great reservoir contact area compared with vertical wells with hydro-fracturing, which is beneficial to the rapid drainage and depressurization of coal reservoirs, causing the peak shifting forward and enhancing economic returns. The horizontal section, extending from the low part of the structure to the high, is conducive to change the gas-water flow characteristics with the gas-water gravity differentiation effect so that water flows to the lower part by gravity effect and gas flows to the high part by buoyancy effect, avoiding the presence of massive gas-water two-phase flow and Jamin effect to consuming reservoir energy, which is particularly advantageous for the development of under-pressured reservoirs. The special wellbore trajectory facilitates on-site workover and drainage management to ensure the continuity and stability of coal reservoir drainage. It is obvious that multi-branch horizontal wells have better technical advantages in developing low-permeability, under-pressure CBM reservoirs, which is the typical ones in China, than vertical well fracturing wells do.

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1 Introduction

As an important unconventional natural gas, coalbed methane (CBM) has attracted quite vast attention of many big coal-producing countries in the past decade [1–12]. China, the largest coal-producing country, has attached great importance to the exploration and exploitation of CBM resources as well as its research since 1990s [13–27]. With the 30 years' ongoing investment of the exploration and exploitation of CBM resources, China CBM industry has achieved great progress, drilling 16855 CBM wells, discovering CBM proved reserve of 685.93 billion cubic meters and obtaining annual production of 4.96 billion cubic meters by the end of 2017. However, there are many difficulties and challenges in the process of development of China CBM industry. Due to the multiple tectonic movements, the main CBM-producing seams in the Carboniferous - Permian coal-bearing formations, underwent deep burial and structural uplift [15, 28], causing high coal rank [15, 23], broken coal structure [29–31], poor permeability [32–34], and serious under-pressure of reservoir [35–39], which brings great challenges to engineering, stimulation and production [40]. In addition, the drilling and completion engineering technology in China is too simple and single, mainly based on vertical wells with the technologies of casing, cementing, perforation and fracturing. The production performance of CBM wells is unexpected low (the average gas production in most development zones is less than 1000 m^3/d) and unstable, leading to poor economic returns of CBM activities [41–43]. In view of the geological characteristics of these coal reservoirs different from those in the United States, Canada and Australia, it often brings about adaptive problems in the process of fully replicating the mature CBM drilling and completion technologies in these countries [41]. Due to the serious structural deformation of coal reservoirs and the low degree of consolidation of coal seams, the coal powder is pumped out easily and seriously, resulting in frequent workovers and uncontinuous drainage, which brings a big challenge to production management. Therefore, it is the key issues for the producers to adopt effective drilling and completion engineering technologies which are suitable for the actual special geological conditions of coal reservoirs, in order to reduce the frequency of workovers and maintain rapid and continuous depressurization of coal reservoirs. Taking a multi-lateral horizontal well in SY block of Qinshui Basin as an example, the unique technical advantages of this well type in CBM development were analyzed by comparing with the vertical well fracturing wells.

2 Geological Background of the Study Area

SY Block studied in this paper, with an area of 1958 km^2, is located on the south-dipping monocline in the north of Qinshui Basin, which is the largest CBM producing basin in China (Fig. 1).

The Permian Shanxi Formation and the Carboniferous Taiyuan Formation are the two important coal-bearing strata in this area. The No. 3 coal seam is deposited in the low part of Shanxi Formation with a thickness of 1–4 m and a buried depth of 400–1600 m, and the No. 15 coal seam is also deposited in the low part of the Taiyuan Formation with a thickness of 3–10 m and a buried depth of 500–1700 m. The spacing between the two main coal seams is about 120 m. The coalbed well tests indicate that most reservoirs have under-pressure with the pressure coefficient of 0.6–0.95 and low permeability with almost less than 1mD (Table 1). According to data tested from the exploration wells, gas content of these coal seams varies from 4.02 to 24.48 m^3/t, and all of these coal seams are unsaturated. The vitrinite reflectance of the coal seams in the block ranges from 1.97% to 2.74% and averages 2.32%. All of these coal seams are characterized by low compressive strength due to tectonic deformation causing by several tectonic movements. The primary present-day maximum horizontal principal stress direction is NE-NNE, showing that the existing dominant natural fracture systems extend in the same direction.

Table 1. The main coal reservoirs characteristics of the study area

Well name	Coal seam	Burial depth (m)	Reservoir pressure (MPa)	Pressure coefficient	Permeability (mD)
A00	3	753.30	4.67	0.63	0.01
A00	15	871.60	4.64	0.54	0.42
A01	3	467.84	2.00	0.44	0.59
A01	9	523.79	2.57	0.50	0.05
A01	15	601.11	2.99	0.51	0.10
A02	3	1054.50	6.30	0.61	0.17
A02	9	1089.30	6.48	0.60	0.25
A02	15	1179.90	6.43	0.55	0.13
A03	15	669.60	2.80	0.42	1.43
A04	15	901.40	5.71	0.64	1.26
A05	15	988.00	6.71	0.68	0.36
A06	3	912.00	6.33	0.70	0.02
A07	9	660.80	1.55	0.24	0.02
A07	15	753.00	3.03	0.41	0.11
A08	9	1161.16	8.27	0.77	0.04
A08	15	1241.00	9.82	0.80	0.13
A09	15	1409.23	7.77	0.56	0.65
A10	15	1416.78	6.48	0.46	0.73
A11	15	1371.65	10.02	0.68	0.48
A12	15	1332.80	7.23	0.54	0.35
A13	15	1412.48	9.11	0.69	0.65

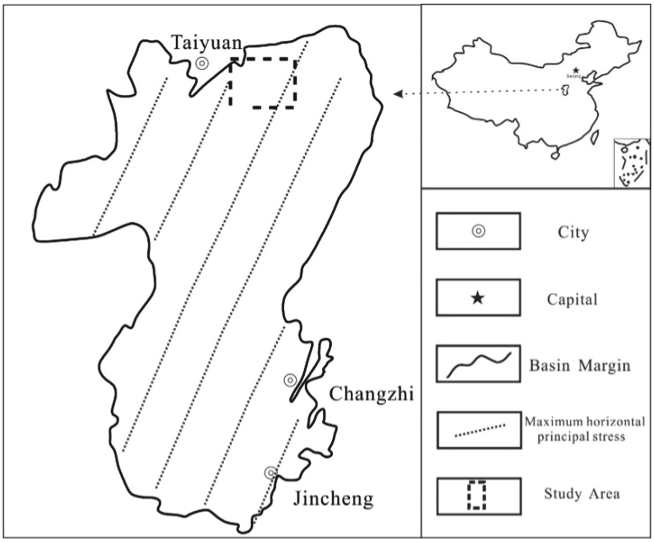

Fig. 1. Map of the qinshui basin and the position of the study area

3 Well Type and Production Performance

More than 400 CBM wells have been drilled in SY block. Most types of the drilled wells are vertical and some are horizontal. But only one multi-lateral horizontal well (namely SY-01H) was drilled in this study area, which was completed in August, 2015 in the north of the block and targeted the No. 15 coal seam in the Carboniferous Taiyuan Formation. The targeted coal is 4.58 m in thickness, 536.8 m in depth, 17.49 m^3/t in gas content and 0.06–0.10 mD in permeability, showing that the target interval has a good resource base but a poor flow ability. The heel of the horizontal well is located in the low part of a structure, while the toes of 8 branches are located in the high part of a structure (Fig. 2). The total footage is 2969.02 m, of which in coal seam is 2488.41 m. The vertical well named SY-01V was jointed with the heel of the horizontal well in the low part of structure. None of the wells were jointed with the toes in the high part of a structure, but several vertical wells were located near those toes.

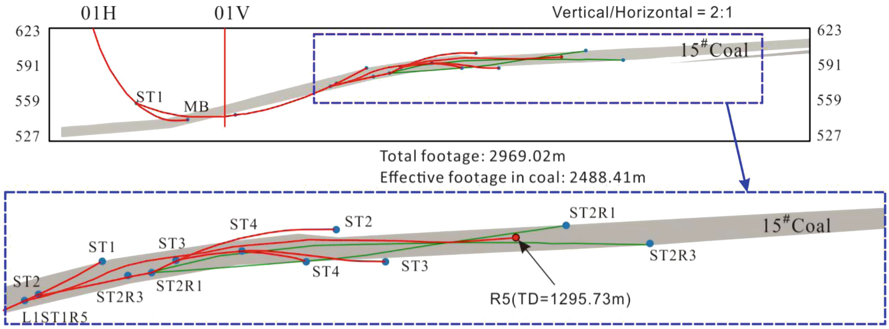

Fig. 2. The wellbore trajectory of multi-lateral horizontal well

The multi-lateral horizontal well and the nearby vertical wells showed different production performance during the past 11-year pumping period. As shown in the Fig. 3, the multi-lateral horizontal well and the vertical well in the low part of structure had higher water production and lower gas production, while those nearby vertical wells in the high part of structure showed lower water production and higher gas production, different from the production performance of those ones far from the toes of the multi-lateral horizontal well.

4 Discussion on the Advantages of the Multi-lateral Horizontal Well in CBM Exploitation

4.1 Increasing the Reservoir Contact Area

Reservoir stimulation is an indispensable technological measure in the CBM exploitation activities due to the coal reservoirs with low porosity and permeability. To date, active water fracturing with large fluid volume mixed sand proppant has been the most dominant coal reservoir stimulation in China. This fracturing technique is mainly characterized by low viscosity fracturing fluids, meaning poor sand transport efficiency. However, ganister sands are usually used as proppant and applied in the active water fracturing activities. Poor sand transport efficiency of frac fluids and high density of frac sands cause sand proppants prone to accumulate in the vicinity of CBM wellbore, leading to a short effective fracture length. Stratigraphic sections of 34 wells, observed in underground coal-mining, demonstrate that frac sands were almost distributed within the 8-m limit around wellbores, showing the garlic-shape, which implied a limited stimulated reservoir volume. Moreover, the accumulation space of frac sands in reservoirs was generated by squeezing the coal, which was certain to compact the coal reservoirs and form a tight annular zone around the frac sands. In short, the vertical wells have not only limit reservoir contact area but also limit stimulated reservoir volume even application of hydraulic fracturing with large fluid volumes.

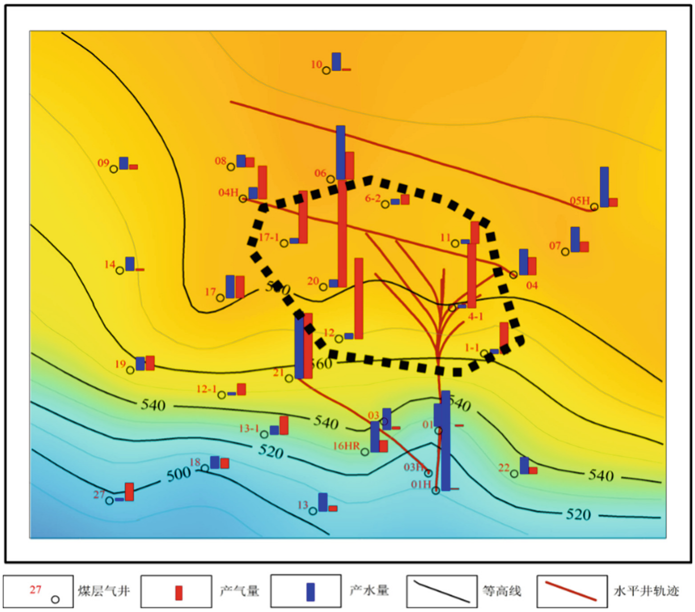

Fig. 3. The production performance of multi-lateral horizontal well and its adjacent wells

Compared to conventional vertical and horizontal wells, multi-lateral horizontal wells (MLHWs) can create more contact area with the reservoir by increase the exposure of the wellbores to the micro-fracture systems of a coal bed and subsequently improving the flow conductivity and enhancing well production and recovery factor, making it an attractive option for efficient exploitation of low permeability reservoirs.

Therefore, it is well known that the significant advantage of multi-lateral horizontal wells is to increase the exposure of a wellbore to the micro-fracture systems of reservoirs, subsequently improving the flow conductivity and enhancing well production and recovery factor. It was proven by the fracturing curve and production performance of well SY-01H. As shown in Fig. 4, oil pressure decreased consistently and slowly during the stable pumping period, meaning that quantities of frac fluids escaped into the reservoir due to the existence of micro-fracture systems in the coal reservoir connecting the wellbore of SY-01H. Additionally, mass cumulative water production volume and high water daily production rate, shown in Fig. 5, demonstrated that the well wellbore was exposed into the micro-fracture systems and the flow conductivity of the coal reservoir has been improved.

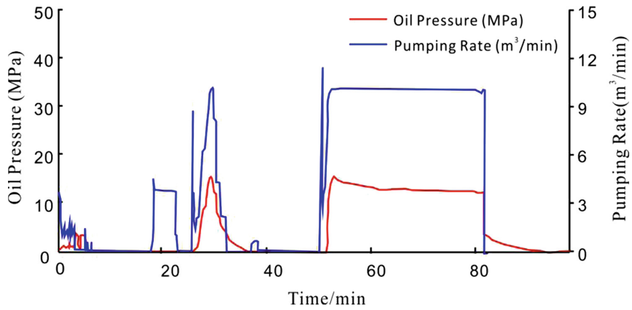

Fig. 4. Fracturing curve of the multi-lateral horizontal well

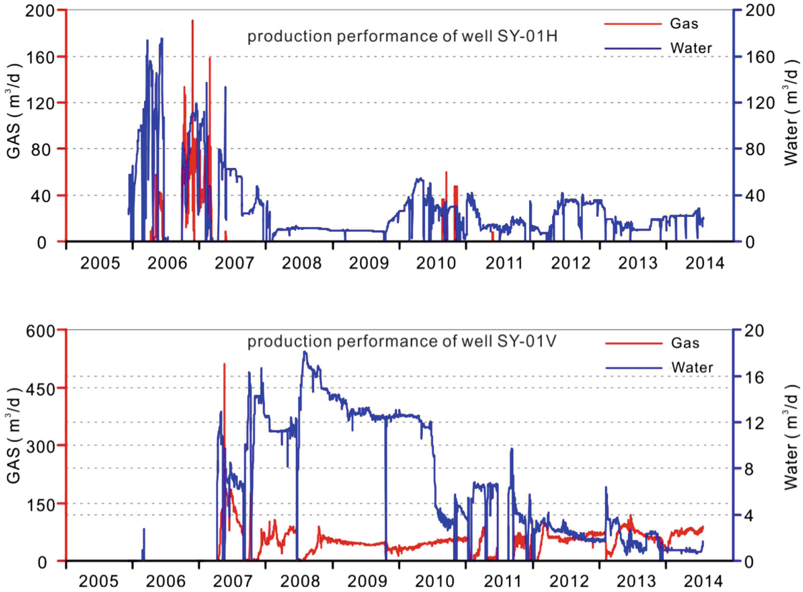

Fig. 5. Production curves of the two wells in the low structure part

4.2 Changing the Reservoir Flow Behavior

Phase behaviors of the typical CBM production profile are distributed with a ring shape, gas-water two phases, unsaturated water phase and saturated water phase in turn from the near to the distance around wellbores in vertical wells (Fig. 6). The gas ratio changes sharply in the different phases, therefore, the mobility for gas and water varies widely, especially in gas-water two phases and unsaturated water phase due to the change of the relative permeability. The distribution of the phase behaviors determines that the coalbed water in the distal end of well control area is prevented to produce, increasing the degree of difficulty in entire depressurization. Besides, the contest mobility of gas and water in the two-phase stage and the capillary pressure existed in the unsaturated water phase stage deplete sharply reservoir energy, which is the adverse effect on CBM exploitation for the low-pressure and under-pressured reservoirs.

Special wellbore trajectory of multi-lateral horizontal well, of which the heel is located in the low part of structure and the toes located in the high part, changes the flow feature of water and gas in coalbed reservoirs. Water flows towards the low part of structure by gravity effect and gas flows towards the high by buoyancy effect due to the existence of tectonic elevation difference between the heel and the toes of the multi-lateral horizontal well, which changes the flow behavior and generates convective motion of gas and water (Fig. 7). The behavior of convective motion differs significantly from the flow feature of vertical wells, rearranging the distribution of phase behaviors inside of reservoirs. This arrangement can improve the flow efficiency of the water and gas phase. It is well known that flow feature varies with the different phase behaviors shown in the typical relative permeability curve. Gas and water flow efficiency is poor and reservoir energy loss is serious in the two-phase flow zone due to the permeability jail [44] near the low cross-over point (Fig. 8). While the two-phase flow is the main flow regime in the reservoirs in the vicinity of the vertical wellbores, which is not conducive to CBM exploitation of the low permeable coal reservoirs. It may be the main reason that production performance of CBM vertical wells in the low permeable reservoirs does not achieve all that expected. However, this situation has been changed when the multi-lateral horizontal wells are applied in the CBM exploitation activities. Water saturation is much greater than gas saturation in the heel of the horizontal well due to gravity effect, maintaining a stable water production rate to depressurize. While gas saturation is much greater than water saturation in the toes of the horizontal well due to buoyancy effect, maintaining a stable gas production rate. Therefore, with the insight of phase behaviors and relative permeability curve, the multi-lateral horizontal wells produce mass water in the low part of structure but mass gas in the high through redistributing the phase behaviors inside the reservoirs, consistent with the actual production performance (Fig. 3).

Redistribution of phase behaviors in the coal reservoirs with the application of multi-lateral horizontal wells can diminish the occurence of the Jamin effect and thus reduce the reservoir energy loss. So this drilling technology is suitable for the low-pressure and under-pressured reservoirs, especially in China. Besides, the desorbed coalbed methane accumulates and pressurizes in the high part of structure to compel water to flow towards the low part due to no wells jointed with toes of this horizontal well, which also can reduce the reservoir energy loss.

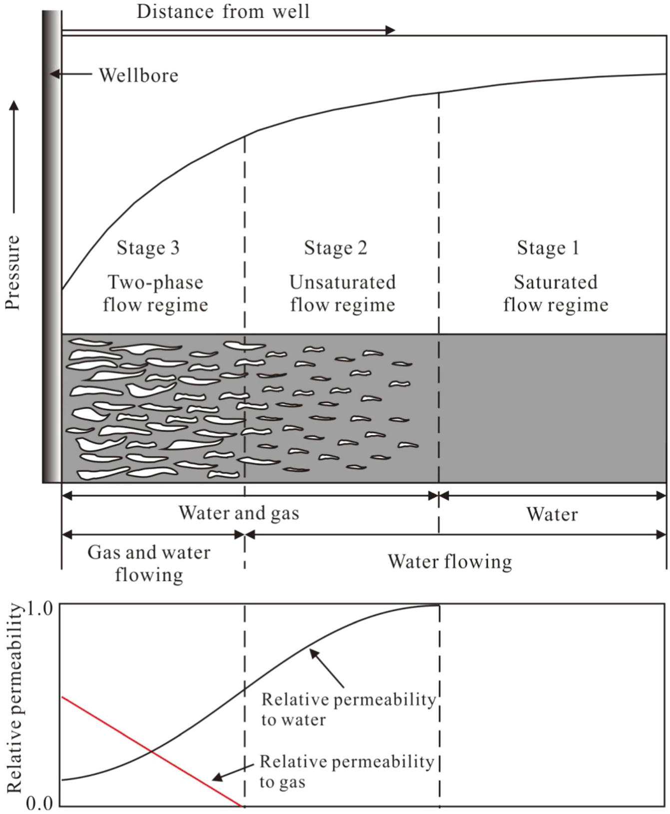

Fig. 6. The flow characteristics of the typical CBM reservoirs

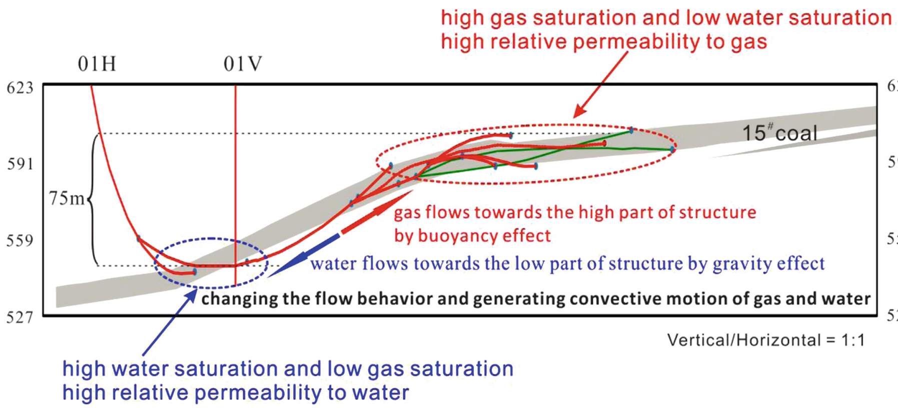

Fig. 7. The flow characteristics and phase distribution affecting by the gas-water gravity differentiation effect

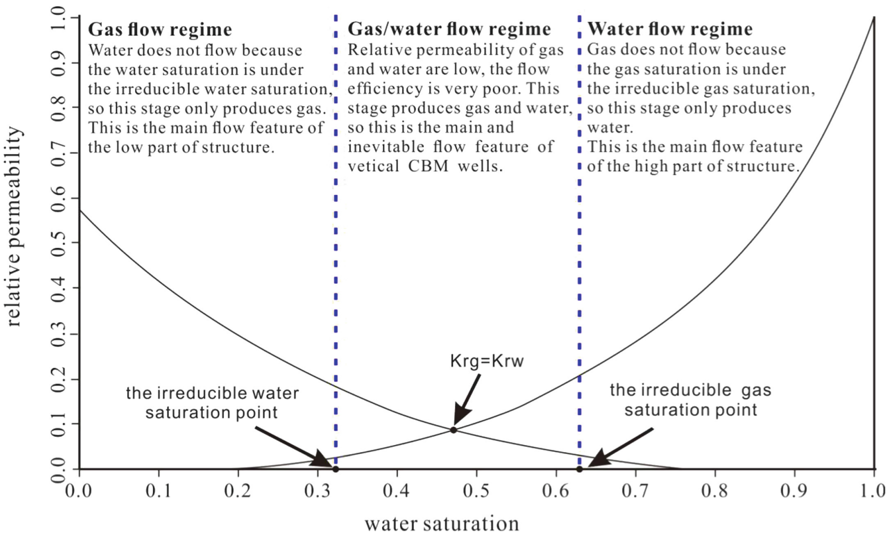

Fig. 8. The flow characteristics with the different phase saturations

4.3 Facilitating On-Site Workover and Drainage Management

During different stages of gas-water production (single-phase water, two-phase gas and water, single-phase gas), the coal fines yield varies greatly. Due to low compressive strength, small Young's modulus and small Poisson's ratio, coal seams tend to fracture and collapse. There are some fragile aggregations inside the coal seams by nature. Combined with coal rock breaking caused by hydraulic fracturing, these aggregations are further sorted under the effect of producing pressure and fluid during CBM drainage, which forms coal fines. The generation of coal fines can easily block fractures in coal seams and reduce the permeability, which in turn influences the overall CBM drainage effect. Especially, coal fines in the pump barrel can wear out the inner surface and affect the pump efficiency, causing stuck pump accidents. In spite of the limited amount of coal fines for most CBM wells, the generation of coal fines will seriously influence the benefits of CBM development. Therefore, study and treatment of coal fines have significance for the improvement of CBM developing efficiency. Statistics show that low production time efficiency with less than 80%, mainly caused by pump stunk due to coal fines, has negative effects on continuous production and performance of CBM wells.

Contrast to vertical wells, multi-lateral horizontal ones have long horizontal segments (about 350 m in SY-01H) and large wellbore storage (Fig. 2). Therefore, the multi-lateral horizontal wellbore trajectory, especially, of which the horizontal segment trending from the low part of structure in heel to the high part of structure in toes, is conducive to retard the reservoir surge due to production incontinuity and reduce the risk of the stunk pump due to the aggregation of coal fines. Besides, the wellbore trajectory can maintain continuous production to depressurize the coal reservoirs because two pumping wells exist in the low part of structure which means that well workover in either well will not affect the production of the other well (Fig. 5).

5 Conclusion

The multi-lateral horizontal well extending from the low part of structure to the high in the study area favors water flowing to the low part and gas flowing to the high part because of the gravity and buoyancy effect in the affected area of the reservoir stimulation and depressurizes the coal reservoirs quickly due to the large contact area of wellbore. The special hole trajectory of the multi-lateral horizontal well not only changes the flow characteristics and the distribution of water and gas inside the coal reservoirs with the gravity and buoyancy effect but also saves the formation energy by decreasing the occurence of Jamin effect, which is very useful for the development of CBM in China because most CBM reservoirs are under-pressured and low-pressure, and which leads to regional rapid drainage and desorption in the coal reservoirs. As a result, the average gas production of vertical wells around the toes of the multi-lateral horizontal well can be as high as 4000 m^3/d or more. Besides, the special wellbore trajectory facilitates on-site workover and drainage management to ensure the continuity and stability of coal reservoir drainage. In short, the technical advantages of multi-lateral horizontal wells in the development of CBM can be listed as follows: increasing the contact area of the reservoir, changing the internal flow characteristics of the coal reservoirs and facilitating on-site workover operations.

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