RESEARCH ARTICLE

Current status and key factors for coalbed methane development with multibranched horizontal wells in the southern Qinshui basin of China

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Abstract
The Qinshui basin is the most successful area for coalbed methane (CBM) development in China. Since 2008, 45 multibranched horizontal wells (MBHWs) have been put into production in the Fanzhuang block, of which 10 wells have an average daily gas rate (DGR) of >10,000 m³/d. Well 4-5 with the total gas production of \(1.054 \times 10^8\) m³ achieved the China’s highest DGR of 63,744 m³/d. Compared with vertical wells, MBHW is an effective way to develop CBM in low permeability reservoirs in China. However, there are still 23 wells with an average DGR of <3000 m³/d, of which 18 wells are below 1000 m³/d. The results show that shallow depth (<600 m), high gas content (>16 m³/t) and saturation (>80%), long coal seam interval (>3000 m), reasonable branch spread, and stable wellbore are the basis for achieving high production. The encountered faults connected to the aquifer will cause a high water production and an extremely low gas rate (<1000 m³/d). In the inclined coal seam, the up-dip MBHW is more favorable for the formation water drainage and the pressure drop funnel expansion than the down-dip MBHW, and the horizontal well should be drilled perpendicular to the high-permeability direction to achieve a higher recovery ratio. MBHW is more sensitivity to drainage rate due to the coal fine migration in the horizontal segments, and the high pressure drop rate will lead to high frequency of stunk pump and eventually affect the gas production. Currently, the biggest challenge for CBM development with MBHW is wellbore stability. 57% of inefficient wells are caused by wellbore collapse during drilling and production processes. Here, a new type of “Roof Drilling-Tree Shaped” horizontal well structure was presented in this work. The first “Roof Drilling-Tree Shaped” horizontal well with a total length of 12,288 m and a coal seam interval of 9408 m was successfully applied without drilling accidents.

KEYWORDS
CBM, multibranched horizontal wells, production, Qinshui Basin, wellbore collapse
1 | INTRODUCTION

China has abundant coalbed methane (CBM) resources and great development potential. According to the latest round of national oil and gas resource evaluation results in China, the geological resources with a depth $<$2000 m are as high as 36.81 trillion m$^3$. CBM resources with a depth $<$1000, 1000–1500, and 1500–2000 m accounted for 38.8%, 28.8%, and 32.4% of the national total, respectively. With the rapid development and utilization of CBM resources worldwide, China is increasingly aware of the importance of such unconventional natural gas. After more than 20 years of exploration and development, by the end of 2017, China has drilled 17,800 CBM wells, including 16,219 production wells with an annual gas production of $49.59 \times 10^8$ m$^3$ (Figure 1). Proven geological reserves (PGR) reached 7000 billion cubic meters (bcm). The Qinshui basin and the eastern margin of Ordos basin are the largest development areas in China, contributing more than 70% of the total PGR. Meanwhile, 9704 CBM wells were drilled in Qinshui basin, of which 9500 are production wells with an annual gas production of 35.5 bcm, accounting to 72% of the national total (Figure 2). The total number of CBM wells in the eastern margin of Ordos basin is 3959, of which 3485 are production wells, with an annual gas production of 11.4 bcm. However, the average daily CBM production in China is only 838 m$^3$/d per well, far lower than other countries, which is the biggest challenge for China’s CBM exploration and development at present. From 2015 to 2017, production wells increased from 12,151 to 16,219, while annual gas production increased by only 10%. A number of investigations related to factors affecting CBM production have been carried out in terms of geology, reservoir properties, and engineering. The complex geological conditions of CBM in China are one of the key factors leading to low production of CBM wells. However, the single development mode is also an important reason that cannot be ignored. Up to now, vertical wells with artificial fracturing technology account to 98% of total CBM wells in

**FIGURE 1** Coalbed methane exploration and development from 2003 to 2017 in China

**FIGURE 2** Coalbed methane exploration and development from 2009 to 2017 in the Qinshui basin of China
China, while the number of horizontal wells is only about 400. Exploring more adaptive and diverse development technologies is critical to the CBM commercial development plans of China.

Generally, vertical well and directional well (including cluster wells, U-shaped horizontal wells, L-shaped horizontal wells, and multibranched horizontal wells (MBHWs)) are two major CBM development modes. MBHW is a technology firstly developed and applied by the CDX Gas LLC in the United States to improve flow conductivity and increases single well production by increasing the exposure of a wellbore to the cleat system. According to Wight, MBHW drilled in coal seams can deplete 1200 acres from a small well site and typically recover 85%-90% of natural gas in 30 months. The branches allow the well to achieve maximum productivity in a short period of time by minimizing the single-water drainage stage. At present, the MBHW has been successfully applied to the CBM development in the Alberta basin in western Canada, the San Juan basin in the United States, and the Bowen/Sydney basins in Australia. In many coal-bearing basins, especially in China where the gas production of vertical wells is poor, MBHW may be an effective way to achieve high CBM production. Ren et al. analyzed the productivities of vertical wells and MBHWs in the Ordis basin of China by numerical simulation. It is concluded that MBHW is more appropriate for CBM resource development due to the larger drainage volume. However, due to the high drilling costs and lack of field gas production data, research on the MBHW adaptation to reservoirs in China is still relatively rare.

**FIGURE 3**

A, Location of the Qinshui basin in China; B, the CBM commercial development blocks in the southern Qinshui basin; C, structural contour map of No. 3 coal seam in the Fanzhuang block; D, The stratigraphic column of coal-bearing formations (modified from Lyu et al.)
Since 2008, PetroChina Huabei Oilfield Company drilled 116 MBHWs in the Fanzhuang block (56 wells) and the Zhengzhuang block (60 wells) in the southern Qinshui basin. The data of 45 MBHWs with production time over 1500 days in Fanzhuang block are collected and presented in this study to: (a) analyze the performance and gas productivity of MBHWs; (b) find the high production indicators and the key factors affecting CBM production; and (c) reveal major problems and challenges in scale promotion and application of MBHW. Finally, a new well type of the “Roof Drilling-Tree Shaped” horizontal well is presented, with the goal of introducing a new CBM development mode and providing some engineering guidance.

2 | GEOLOGICAL SETTING

Coal seams in the Qinshui basin belong to Carboniferous and Permian period. Affected by the Yanshan movement, the basin is a large Synchinorium located in the northeast direction. The prospective reserve of coal seams is about 300 billion tons with an area of 23,503 km² (Figure 3B). The geological CBM resources of depth <1000, 1000-1500, and 1500-2000 m are 20.808.87 × 10^8 m³, 9950.51 × 10^8 m³, and 8741.04 × 10^8 m³, respectively. Coal seam No. 3 of the lower Permian Shanxi Formation and coal seam No. 15 of the upper Carboniferous Taiyuan stratum are recognized as the stable and exploitable seams in the area. The thickness of the Shanxi stratum is 20-90 m, which is composed of sandstone, siltstone, mudstone, and coal seam (coal No. 1, No. 2, and No. 3). The Taiyuan Formation has a thickness of 50-35 m and is composed of limestone, sandstone, siltstone, mudstone, and coal (coal No. 5, No. 6, No. 7, No. 8, No. 9, No. 11, No. 13, No. 14, No. 15, and No. 16). The average thickness of the target seams is 5.8 m. During the Yanshan movement, the Qinshui coalfield appeared in an embryonic form. Strong magmatic activity resulted in an increase of terrestrial heat, which raised the coal rank to the present levels. Present-day gas content is controlled by the combination of tectonic, sedimentary, and hydrodynamic characteristics, typically between 10 and 25 m³/t (mostly are undersaturated coals). The average ash yield, moisture content, and volatile matter content are 11%, 1.05%, and 10.26%, respectively. The coal composition is primarily the vitrain and the clarain with some durian. Lithotype is bright to semibright. The tectonic characteristics of the basin are relatively simple with general folds and few faults. In the southern part of the Qinshui basin, Sitou fault and Houchengyao fault in the NE-SW direction are two major faults. The Fanzhuang block and the Zhengzhuang block with the total area of 639 km² are the two largest CBM development zones in the Qinshui basin. By the end of 2017, 2193 production wells were drilled in two blocks, with a daily gas output of 147.16 × 10⁴ m³. The Fanzhuang block is the study area for this work (Figure 3C).

3 | MBHW STRUCTURE AND WELL-RUN BRIEFS

Multibranched horizontal well was drilled as a fishbone patterned horizontal multilateral through the coal seam No. 3 in the Fanzhuang block with an aim of dewatering and thereby depressurize the coal seam and extract CBM. Here, MBHW incorporates one vertical well and a multilateral well.
consisting of two main laterals with several fishbone multilaterals (Figure 4A). The vertical well for discharging water and collecting methane that in front of multilateral well was drilled firstly with a drilling mud system and cased with a fiberglass tube. After cementing, an artificial cavity will be made in 3# coal for intersection. Using the vertical well, modeling can be done before starting drilling to simulate log responses across the target coal seam. Multilateral well was drilled with a bottom-hole assembly containing a positive displacement motor for steering and IMPULSE tool to record GR azimuthal and resistivity. The logs recorded during drilling were correlated with the modeled logs to dynamically refine the gesturing model. This was a continuous process, executed throughout the drilling operation using real-time Geosteering Software and Drilling Office to aid in making the appropriate steering decisions. Underbalanced drilling technology was used in this multilateral well (The air was injected from vertical well to the annular of the multilateral well we were drilling, and a rotary BOP was installed on this horizontal wellhead). The solid-free polymer (freshwater with carboxymethyl cellulose) was the drilling fluid used for laterals (with open-hole completion).

Taking well group 4 as an example, it is a trifurcate multilateral horizontal well group which is composed of five multilateral horizontal wells and five corresponding vertical wells (intersection wells), altogether with 10 main holes and 29 laterals in coal seam (Figure 4B). The Well 4-5 incorporates one vertical well (Well 4-5V) and a single fishbone (Well 4-5H) consisting of two main laterals (M1 and M2) with six fishbone multilaterals (L1, L2, L3, L4, L5, and L6). The Well 4-5V was firstly drilled through the coal seam No. 3 and cased with a fiberglass tube. After cementing, an artificial cavity (with diameter of 0.5 m) was made in coal seam No. 3 for intersection. The Well 4-5H was spud around 219.8 m away from Well 4-5V. First lateral will be drilled, and then, the deviated open-hole section drilled by Schlumberger will be landed on top of the coalbed and intersected with the vertical well using RMRS (rotation magnetic range system). This lateral, defined as the mainbore1(M1), was then continued to drill 777 m after succeeded intersection at 646 m. L1, L2, and L3 start to sidetrack from M1 at 1090, 954.4, and 815 m, respectively. The M2 start to sidetrack from 680 m tie in to M1 borehole, and the total 893 m of the M2 section was drilled after trenched from the M1 hole. Then, L4, L5, and L6 start to sidetrack from M1 at 1180, 995, and 816 m, respectively. The total length of section drilled from landing point was 5071 m, and the well was geosteered within the target coal seam over an interval (CSI) of 4864 m, 207 m out of the target.

| Well no. | Branch | CSI (m) | Well No. | Branch | CSI (m) | Well no. | Branch | CSI (m) |
|---------|--------|---------|----------|--------|---------|----------|--------|---------|
| Well 1-1 | 2/6    | 5482    | Well 5-1 | 2/7    | 2570    | Well 11  | 2/7    | 3296    |
| Well 1-2 | 2/4    | 2729    | Well 5-2 | 2/13   | 4579    | Well 12  | 2/6    | 4563    |
| Well 1-3 | 3/7    | 4872    | Well 6-1 | 2/6    | 4177.9  | Well 13  | 2/9    | 2948    |
| Well 1-4 | 2/6    | 5186    | Well 6-2 | 2/6    | 4042    | Well 14  | 2/13   | 2687.5  |
| Well 1-5 | 1/8    | 3976    | Well 7-1 | 2/6    | 4531    | Well 15  | 1      | 511     |
| Well 2-1 | 4/7    | 2861    | Well 7-2 | 2/2    | 863.85  | Well 16  | 2/9    | 3761    |
| Well 2-2 | 3/6    | 2636    | Well 8-1 | 2/6    | 3943    | Well 17  | 2/13   | 3309    |
| Well 2-3 | 2/10   | 3766    | Well 8-2 | 2/8    | 3366.5  | Well 18  | 2/10   | 2306    |
| Well 3-1 | 2/8    | 5050    | Well 8-3 | 2/5    | 4212    | Well 19  | 2/12   | 3451    |
| Well 3-2 | 2/6    | 5583    | Well 9-1 | 2/4    | 2605    | Well 20  | 2/11   | 1563.9  |
| Well 4-1 | 2/6    | 3609.28 | Well 9-2 | 2/6    | 3900    | Well 21  | 2/8    | 3416.5  |
| Well 4-2 | 2/6    | 4577    | Well 9-3 | 2/5    | 3885.76 | Well 22  | 2/8    | 4604    |
| Well 4-3 | 2/6    | 4061.5  | Well 10-1| 2/9    | 3195    | Well 23  | 2/6    | 4489    |
| Well 4-4 | 2/5    | 4908    | Well 10-2| 2/6    | 3502.23 | Well 24  | 2/10   | 4213    |
| Well 4-5 | 2/6    | 4683    | Well 10-3| 3/7    | 3898.76 | Well 25  | 2/11   | 4356    |

4 Branch = the number of main holes/the number of laterals.

Coalbed methane production is a long-term drainage process with continuous pressure reduction and gas desorption. SUP"
The production practice in the Fanzhuang block shows that the MBHW production cycle generally exceeds 6 years (Figure 5). Similar to vertical wells, MBHW production can also be divided into four stages: Stage I represents the single-water drainage stage, with the aim of reducing formation pressure to reach desorption pressure of coal seams. In Fanzhuang block, this stage will take 0-632 days (averaging 103 days), usually from 0 to 100 days. In stage II, the CBM starts to desorb and the wells will reach the maximum gas production in 10-30 months (averaging 15 months). The fact that the coals are undersaturated probably explains the long time required for gas production to of some wells. Stage III represents a stable production stage whose duration depends on the single well control area and the abundance of CBM resources (gas content and coal thickness). For high production wells, stage III will last for 2-4 years, longer than vertical wells. For stage IV, the desorbable gases in coal matrix begin to decrease, and both gas production and water production are declining.

When the formation pressure within the well control range drops to the depletion pressure, the well will lose its economic value. This stage lasts for a long time of more than 3 years.

The gas and water production of 45 MBHWs are plotted in Figure 6. The maximum daily gas rate (MDGR) is between 628 and 63 744 m³/d with an average of 14 748 m³/d. The average daily gas rate (DGR) ranged from 173 to 40 913 m³/d, averaging 6920 m³/d. Well 4-5 with the total gas production of $1.054 \times 10^8$ m³ in 2660 d reached the China’s highest DGR of 63 744 m³/d. The total daily gas production of 125 vertical wells adjacent to those MBHW is also collected and is about $14.08 \times 10^4$ m³/d, with an average DGR of 1126 m³/d per well. From the perspective of economic efficiency, the average investment of horizontal well is $1.3$ million per well and is about 5.35 times that of a single vertical well investment ($0.24$ million), while the average DGR of MBHW is about 6.15 times that of the vertical well. Also, MBHW has a longer production cycle.
and cumulative production, with great production potential. In this work, the average DGR of MBHW is divided into high production wells (HPW) with DGR >10 000 m³ and MDGR >20 000 m³, medium-high production wells (MHPW) with DGR >6000 m³ and MDGR >10 000 m³, and medium production wells (MPW) with DGR >3000 m³, low production wells (LPW) with DGR >1000 m³, and extremely low production wells with DGR ≤ 1000 m³ (ELPW). Among 45 MBHWs, there are 10 HPW (averaging DGR of 22 400 m³/d per well), five MHPW (averaging DGR of 7692 m³/d per well), seven MPW (averaging DGR of 4239 m³/d per well), five LPW (averaging DGR of 1884 m³/d per well), and 18 ELPW (averaging DGR of 787 m³/d per well). Overall, MBHW is an efficient means of CBM development, but further optimization is needed to reduce the percentage of low production gas wells.

5 | HIGH PRODUCTION INDEXES AND KEY FACTORS FOR CBM PRODUCTION WITH MBHW

5.1 | Production indexes for high production wells

The gas production curves of HPW are plotted in Figure 7, which show that all HPV appear to be unimodal with one major peak. The maximum gas rate is 19 220-63 744 m³/d, averaging 42 796 m³/d per well. The single-water drainage stage ranges from 0 to 180 days with an average of 75 days. There are no single-water drainage stages for Well 17, Well 22, and Well 25, suggesting the presence of free gas in cleats or fractures. Moreover, the flowing bottom-hole pressure (FBHP) at the moment that the casing pressure appears can be regarded as the approximate desorption pressure of the coal seam. Here, the approximate desorption pressure of HBW is between 1.807 and 2.627 MPa, mean 2.14 MPa. Furthermore, the ratio (RDR) of the desorption pressure to the reservoir pressure is more meaningful and comparable. According to Chen et al., there is a linear positive relationship between reservoir pressure measured with well testing and depth, which can be used to calculate the reservoir pressure of coal seams in each MBHW. The results show that the RDR of HPV ranges from 0.5 to 0.99, with an average of 0.78.

To make it more clearly, the scatter plot between average depth, CSI, RDR, and DGR of 45 MBHWs is shown in Figure 8. With increasing depth, the productivity decreases gradually, and coal reservoirs with a depth of typically <500 m have the best production potential. When the depth >600 m, the average DGR of most wells is <1000 m³/d per well. This is related to the decrease in permeability, particularly in study area with high in situ stress levels. The CSI of MBHW is an important engineering parameter that determines the control area and drainage volume of each well. Figure 8B indicates that MBHW with a CSI < 3000 m always has a low gas rate. However, there are also some MBHWs with a CSI > 5000 m show poor production capacity, which is related to gas content, drainage control system, fault, branch angle, and spacing and is further discussed in Section 5.2.2. Figure 8C suggests that a positive relationship exists between the RDR and the average DGR, and coals with RDR < 0.5 have poor CBM productivity. Similar to vertical wells, the high water production (>10 m³/d) of MBHW means low gas production, because a large amount of formation water makes it difficult to reduce reservoir pressure and result in a smaller pressure drop range (Figure 8D).

5.2 | Key factors affecting gas production of MBHW

In this part, the specific reasons for the failure to achieve high CBM production of MBHW are further analyzed from the perspective of geological, engineering, and drainage control methods. Factors in the analysis include faults, drilling and completion, wellbore collapse and branch spread, branch inclination and direction, drainage velocity, and coal fine migration. Finally, the key factors and main challenges form CBM development with MBHW at current status are proposed.

5.2.1 | Faults and gas content

Coal seam structural conditions, especially fault development, have an important impact on the production of MBHW. In the Qinshui basin, there are three sets of aquifers that are not connected in the longitudinal direction, and the Ordovician limestone aquifer is rich in water. The height between the Permian Shanxi Formation 3# coal seam and the Ordovician limestone aquifer is only 50–70 m, which are easy to communicate with each other by faults. Once
fault connected with aquifer is encountered by laterals, the reservoir pressure will be difficult to drop down due to the presence of a large amount of formation water and thus result in the limited pressure drop funnel. This type of MBHW is typically characterized by ELPW and is represented by Well 3-1. Well 3-1 consists of two main bores and eight laterals, with CSI of 5050 m. During drilling process, about 30 different-scale faults were encountered, and five faults were encountered by L1. As a result, the cumulative water production during single-water drainage stage reached 20,440 m$^3$. After 2070 days of production, the total water production of WELL 3-1 reached 71,533 m$^3$, with an average water rate of 27 m$^3$/d (Figure 9). The high water production leads to a limited desorption area, and the average DGR is only 260 m$^3$/d. Also, the faults encountered by the branch will lead to unexpected abrupt regional dip changes of well trajectory, resulting in low coal seam drilling rate, high risk for drilling, and wavy-shaped well trajectory.

High gas content always means high production potential, and the measured gas content and gas saturation of HPW are $>16$ m$^3$/t and 80%, respectively. However, faults may provide passageway for the escape of CBM, resulting in low gas content and a low gas rate of CBM wells. Well 6-2 was drilled smoothly with CSI of 4042 m, and faults were encountered by M1, M2, L1, L4, L3, and L5. The gas and water production curves of Well 6-2 are shown in Figure 10. The gas production reached the maximum gas rate of 1600 m$^3$/d after 1700 days and then exhibits a decreasing trend, reflecting a low amount of desorbable gases in coal matrix. Generally, the production of this type MBHW is characterized by low gas rate and low water rate without a stable production phase.
5.2.2 | Wellbore stability and branch spread

Unlike other unconventional natural gas reservoirs such as shale gas reservoir and tight sandstone gas reservoir, coal reservoirs have unique cleat systems including face cleat and butt cleat, with complex mechanical strength influencing well stability in horizontal boreholes.7,16,20,39-47 Also, the horizontal sections here were drilled with the solid-free polymer as the drilling fluid and completed with open hole, which may prone to collapse during drilling and production.48-50 The influence of wellbore stability on MBHW production during drilling process is mainly reflected in the single well control area, which is embodied in the two parameters of CSI and branch spread. The collapse of main bores will lead to a small CSI, and Well 15 is the most typical example. Well 15 was designed to have two main bores and six laterals. However, after succeeded intersection at 828 m, the serious collapse of the coal seam occurred at 850 m, and drilling project must be completed ahead of time. As a result, the CSI of this well is only 511 m and is mainly distributed between engineering well and vertical production well, resulting extremely low gas production of 173 m³/t (Table 1 and Figure 6).

At the present, the most common in southern Qinshui basin is unexpected branch spread caused by coal collapse during drilling process. When the coal seam collapses, two measures are usually taken. The first is to complete the well ahead of time, such as Well 7-2 and Well 1. Generally, the maximum gas production of the type wells is lower than 3000 m³/d due to small well control area and limited desorption potential (Figure 11). The second is side track from other locations and drill more laterals than plan to increase CSI, such as Well 14. The Well 14 was designed with two main bores and six laterals, and it has two main bores and 13 laterals according to actual trajectory. The lateral is mostly gathered together with small spacing and high density, which enables the CBM with low permeability (or absence of an effective cleat system) to be transported to the vertical production well. Therefore, the well reached the maximum gas rate of 16763 m³/d in short time due to pressure drop coupling from near laterals. However, the pressure drop is difficult to progress and extends to the far well zone, and thus, the gas production cannot be maintained at a high level and will gradually decrease and eventually stabilize at relatively low gas production (4000 m³/d).

Furthermore, all the horizontal wells are open-hole completion at present, without casing or screen. In the production process, instability of wellbore affected by coal structure, in situ stress, and depth may cause wellbore collapse.41,51-55 The specific performance of wellbore collapse during production process is a sudden linear decline in gas production, for example, Well 1-4 (Figure 12). The gas content, gas saturation, depth, and CSI of coal seams in Well 1-4 are 17.4 m³/t, 88.4%, 586.65 m, and 5186 m, respectively, which have great production potential. The CBM desorbed quickly, and the gas rate increased sharply in the initial stage. However, due to the wellbore collapse, the gas production suddenly decreased linearly when the gas rate reached 4200 m³/t and eventually remained within 500 m³/t. Another strong evidence is that the produced water suddenly changed from clear water to dark gray water with a large amount of coal fines.
5.2.3 | Branch inclination and direction

Due to the flow resistance in the horizontal wellbore, the longer the horizontal section, the greater the energy required to overcome the internal resistance of the flow. For inclined coal reservoirs, due to the influence of gravity on water migration, the reservoir pressure of up-dip horizontal well and down-dip horizontal well will decrease asymmetrically, which will lead to different productivity. In this work, the productivity of up-dip horizontal well and down-dip horizontal well was compared according to the actual production curve and we found that the up-dip horizontal well results in a better water drainage. The up-dip well (Well 1-1) and down-dip well (Well 1-2) were drilled from the same drilling platform, with opposite drilling direction. Those two wells have reasonable branch spread and are adjacent to the well group 4, where the gas content, gas saturation, and depth of the coal seam can meet the requirements of high-yield wells. The CSI of the up-dip well and down-dip well is 4482 and 4729 m, respectively. After
a production duration of 2500 days (Figure 13), the average DGR of up-dip well is 7950 m³/d, which is twice that of the down-dip well (3562 m³/d). The maximum gas rate of Well 1-1 reached 14 000 m³/d, while that of down-dip well is 6500 m³/d. Also, there are some differences in water production before desorption. The total water production of up-dip well within single-water drainage stage (73 days) is 608.3 m³, while that of down-dip well is 239.2 m³ (within 78 days).

A large number of previous studies have shown that the up-dip drilling direction in inclined coal seams makes the better gas and water production. For CBM development in inclined coal reservoir by vertical wells, Kang et al. found that CBM in inclined coal seams of Fukang west block can be desorbed early in the up-dip direction reservoir and the change rate of the gas content in the up-dip direction reservoir is greater than that in the down-dip direction reservoir. Based on the numerical simulation, Fu et al. believe that the pressure drop rate of the up-dip coals is greater than that of the down-dip coals, and thus, the gas content in the up-dip direction decreases faster than that of the down-dip direction. For horizontal wells, the production is mainly contributed from the up-dip orientation. Actually, the difference between them is mainly from the gas and water migration caused by the effect of gravitational potential energy. For up-dip wells in inclined coal seams, gas migrates toward the higher region due to the effect of the difference in gas and water density, while the formation water in the upper coal seam is more likely to flow to the wellbore under the action of gravity potential energy (Figure 14). However, when the branch is in down-dip direction, the water of each branch is difficult to flow to the cavity well, and the down-dip wellbore will be filled with liquid even if the dynamic liquid level is reduced to the coal seam, resulting in lower drainage efficiency and slower pressure drop rate. Therefore, the up-dip MBHW is more favorable for CBM development.

In addition, due to the open-hole completion, these horizontal wells cannot carry out the hydrofracturing to increase permeability. Therefore, the well trajectory should be orthogonal to the face cleat direction, meaning that the horizontal well should be drilled perpendicular to the high-permeability direction, which is beneficial for the horizontal well to maximally penetrate the face cleats and communicate with high-permeability face cleats. These can greatly improve the pressure drawdown in the reservoir and result in a higher recovery ratio from horizontal wells. For hydrofractured horizontal wells, the well trajectory should be as perpendicular as possible to the direction of the maximum principal stress, and the tensile stress region is preferred. This is beneficial for the segmented fracturing of the horizontal well to form a long fracture if hydraulic fracturing is used.

5.2.4 | Coal fine migration

In the drilling process of CBM horizontal wells, some coal fines remain in the horizontal wellbore. During production process, a large amount of coal fines will be produced due to the scouring and shearing action of the water flow and be moved into the wellbore. Generally, the coal fine migration in the horizontal wells will be more sensitive than that in the vertical wells due to the existence of horizontal section, and there is a critical startup flow velocity for coal fine migration. Over this critical flow velocity, fine migration will cause major (and expensive) problems with the pumps. Up to now, 99% of the pumping operation in MBHW of Fanzhuang block is caused by the coal fine stuck pump. The high stuck pump frequency not only interrupted the continuity of production, but also brought huge costs. Well 4-2 and Well 4-4 are two MBHWs from well group 4 (Figure 4B), with an average DGR of 8000 and 8500 m³/d, respectively, which is less than that of Well 4-1 (12 064 m³/d), Well 4-3 (25 497 m³/d), and Well 4-5 (39 658 m³/d). For Well 4-2, the drop rate of working fluid level is 1.8 m/d at the depth of 196-425 m, while that of Well 4-3 is only 0.7 m/d. The faster drainage rates increase the water flow energy and allow coal fines to migrate to the vertical production wells, leading to several times stuck pump in the early production stage (within 300 days; Figure 15). The produced water in this stage was characterized by dark
FIGURE 15  Production profile of Well 4-2

[Graph showing production profile with water rate (m³/d) and gas rate (m³/d) over production time (d).]

DISCUSSION AND SUGGESTION

Based on the analysis of 35 low-efficiency wells (DGR < 10 000 m³/d), we found that geological factors, engineering factors, and drainage control can affect the single well productivity of multibranch horizontal wells. The geological factors mainly include encountered faults and low gas content. The engineering factors consist of wellbore collapse, branch spread, coal seam interval length, and branch inclination. The influence of drainage control on gas production is mainly caused by coal fine migration. The most important factors for the failure to achieve high production of each well are counted in Table 2. The MHPWs always have the great production potential with high maximum gas rate, but influenced by branch inclination and coal fine migration, the wells exhibit a gas rate lower than the HPW. The damage of coal fine migration and discontinuous production in the early stage on expansion of the pressure drop funnel is unrecoverable. When the encountered faults connected with aquifer or coal seams are characterized by low gas content, the MBHW will have a low or extremely low gas production. For low gas content, the gas production is also characterized as the unimodal, but with the small peak value. Once the branch encounters the faults that connect to the aquifer, the total water production will be >15 000 m³, resulting that CBM is difficult to desorb and a limited well control area. The well collapse during drilling process will cause small CSI or unreasonable branch spread, while well collapse during production process will lead to a sudden linear decline in gas production. Overall, the biggest challenge for CBM development with MBHW at present is from engineering factors, especially for the wellbore stability. Among 35 wells, there are 20 MBHWs affected by wellbore collapse, accounting to 57% of the total, and 67% of the ELPW were caused by this.

Currently, exploring some new methods to ensure the stability of the borehole wall is an urgent problem to be solved in the development of China’s CBM. Underbalanced drilling may be wrong method to drill these wells. They will have to be drilled in an overbalanced mode, with a drilling mud system that will allow the formation of a filter cake and prevent the well for collapse until a liner can be inserted. Also, the MBHW structure incorporates one vertical well and a multilateral...
A well, and multilateral well is required to dill along coal seam. However, the unstable characteristics of coal seams in China result in the high frequency of drilling accidents. In particular, when the main wellbore collapses, the well has to be finished drilling ahead of time, causing a small CSI and limited well control well. To ensure that the main wellbore is stable, a “Roof Drilling-Tree Shaped” MBHW structure designed and applied by Huabei Oilfield Company of PetroChina is presented in this work (Figure 16). The “Roof Drilling-Tree Shaped” wells incorporate two vertical wells and a multilateral well consisting of one main wellbore (trunk) with several secondary laterals (bough) and many tertiary laterals (twigs). The vertical wells are used for discharging water and collecting methane. The trunk is drilled along the coal seam roof.

### TABLE 2  
The most important factors for each inefficient well in Fanzhuang block

| Key factors                      | MHPW | MPW | LPW | ELPW | Total |
|----------------------------------|------|-----|-----|------|-------|
| **Geological**                   |      |     |     |      |       |
| Faults + Low gas rate            | 0    | 0   | 1   | 2    | 3     |
| Faults + High water production  | 0    | 0   | 0   | 4    | 4     |
| **Engineering**                  |      |     |     |      |       |
| Wellbore collapse during drilling | 0    | 3   | 1   | 6    | 10    |
| Wellbore collapse during production | 0   | 1   | 3   | 6    | 10    |
| Branch inclination               | 2    | 2   | 0   | 0    | 4     |
| **Drainage control**             |      |     |     |      |       |
| Coal fine migration              | 3    | 1   | 0   | 0    | 4     |

**FIGURE 16**  
The diagram of “Roof Drilling-Tree Shaped” multibranched horizontal well structure

**FIGURE 17**  
The trajectory and well structure of Well ZS1-5 in southern Qinshui basin
or floor to ensure wellbore stability, and is the main channel that gathers CBM and water from both bough and twigs. The boughs (6-12 in number, 200-400 m in length, and 100-200 m in space) are drilled from the trunk into coalbeds to achieve the large well control area and are the connecting channels of trunk and twigs. Here, putting the well path above the higher position of the target coalbed to avoid touching the lower soft coal is more important than ensuring high coal seam drilling rate, because a large number of twigs (18-36 in number, 100-200 m in length, and 50-100 m in space) drilled from the bough are the main channels of gas production (Figure 16B). In order to ensure long-term stability of the cave, the cavity of the vertical wells is also built on a stable roof (or floor) and is at the lower part of the main wellbore trajectory.

Huabei Oilfield Company carried out a test well of “Roof Drilling-Tree Shaped” MBHW in the southern Qinshui basin to detect its stability (Well ZS1-5), which incorporates two vertical wells (ZS1-5V1 and ZS1-5V2) and a multilateral well (ZS1-5H) consisting of one trunk with 13 boughs and 26 twigs, with cost of $4 million (Figure 17). The total length of Well ZS1-5 is 12 288 m, which cover a coal seam interval of 9408 m, which has set a domestic record in China. There is no drilling accident occurred during drilling process. After 600 days of production, the gas rate of well ZS1-5V1 has now reached 10 000 m³/d, while that of ZS1-5V2 is 3100 m³/d. It is worth noting that the gas rate of vertical wells around the well ZS1-5 is lower than 100 m³/d or most of which produce water worth noting that the gas rate of vertical wells around the well ZS1-5V2 further confirmed that the gas productivity is only. In addition, the difference in gas rate between ZS1-5V1 and ZS1-5V2 further confirmed that the gas productivity is more effective when the production vertical well is located in the lower region of inclined coal seam. Furthermore, the promotion and application of “Roof Drilling-Tree Shaped” MBHW in the development of CBM can also reduce the number of conventional vertical or directional wells and save the land occupation of the well site, which should be paid more attention in future CBM development plan.

7 CONCLUSION

1. The average daily gas rate of MBHW is 6920 m³/d per well and is 6.15 times of the vertical wells. Well 4-5 with the total gas production of 1.054 × 10⁸ m³ within 2660 days reached the China's highest DGR of 63 744 m³/d. The high production wells appear to be unimodal with one major peak and long-term stable production stage. Therefore, MBHW is an effective way to develop CBM in low permeability coal reservoirs in China. However, 70% of MBHWs did not achieve high gas production (>10 000 m³/d), and 40% of which have a gas rate below 1000 m³/d.

2. Shallow depth (<600 m), high gas saturation (>80%), long coal seam interval (>3000 m), reasonable branch spread, stable wellbores, and the “slow, continuous, and stable” drainage control system are the basis for achieving high production. The encountered faults that connect with the aquifer will cause a high water production and an extremely low gas rate. In inclined coal seams, the up-dip MBHW is more conducive to the formation water discharge and the pressure drop funnel expansion than the down-dip MBHW due to the effect of gravity.

3. The biggest challenge for CBM development with MBHW at present is wellbore stability caused by coal physical property, underbalanced drilling, drilling fluid used, and open-hole completion. The well collapse during drilling process will cause a small CSI or an unreasonable branch spread, while well collapse during production process will lead to a sudden linear decline in gas production. Among 35 low-efficiency wells, there are 20 MBHWs affected by wellbore collapse, accounting to 57% of the total. In the nearly future, the wells have to be drilled in an overbalanced mode, with a drilling mud system (or with the proper drilling fluid composition) that allow the formation of a filter cake and prevent the well for collapse until a liner can be inserted.

4. The “Roof Drilling-Tree Shaped” well incorporates two vertical wells and a multilateral well consisting of one trunk with several boughs and many twigs. The trunk is drilled along the coal seam roof or floor to ensure wellbore stability, while twigs are the main channels of gas production. The boughs determine the well control areas and are the connecting channels of trunk and twigs. The successful pilot development of this new type of well has been achieved in the south Qinshui Basin and deserves more attention in the future CBM development plans.

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