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REVIEW

Drilling and completion technologies of coalbed methane exploitation: an overview

Tianshou Ma[1] · **Jinhua Liu**[1] · **Jianhong Fu**[1] · **Bisheng Wu**[2]

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Abstract

Coalbed methane (CBM) drilling and completion technologies (DCTs) are significant basis for achieving efficient CBM exploration and exploitation. Characteristics of CBM reservoirs vary in different regions around the world, thereby, it is crucial to develop, select and apply the optimum DCTs for each different CBM reservoir. This paper firstly reviews the development history of CBM DCTs throughout worldwide and clarifies its overall development tendency. Secondly, different well types and its characteristics of CBM exploitation are summarized, and main application scopes of these well types are also discussed. Then, the key technologies of CBM drilling (directional drilling tools, measurement while drilling, geo-steering drilling, magnetic guidance drilling, underbalanced drilling and drilling fluids), and the key technologies of CBM completion (open-hole, cavity and under-ream completion, cased-hole completion, screen pipe completion and horizontal well completion) are summarized and analyzed, it is found that safe, economic and efficient development of CBM is inseparable from the support of advanced technologies. Finally, based on the current status of CBM development, the achievements, existing challenges and future prospects are summarized and discussed from the perspective of CBM DCTs.

Keywords Coalbed methane · CBM · Exploitation · Drilling · Completion · Horizontal well · L/U/V-shaped well · Multilateral well

1 Introduction

Coalbed methane (CBM), is also known as coalbed gas and coal seam gas/methane (CSG/CSM), which are terms referring to the unconventional natural gas resource stored in coal beds and are expected to be an important energy resource of global significance in the future (Rightmire 1984; Rice 1993; Flores 1998, 2013; Palmer 2010; Yang and Liu 2021). Nowadays, the commercial exploitation patterns of CBM have been successfully established in some countries throughout the world (Moore 2012; Qin et al. 2018; Li et al. 2018; Tao et al. 2019; Lu et al. 2021), mainly including the United States, Australia and China, and the CBM production history of which is shown in Fig. 1 (EIA 2022; National Bureau of Statistics 2022; Australian Government 2022).

As is well known, the commercial development of CBM originated from several major gassy basins in the United States since 1990s, such as the San Juan, Black Warrior, and Powder River, and it had already achieved a great success in a very short time. However, it can be clearly seen from Fig. 1 that the CBM production in the US has declined gradually since the peak of 55.6 billion cubic meters (Bcm) in 2008 (EIA 2022), which is mostly caused by the boom and success in the shale gas exploitation (Li et al. 2018). But it is worthwhile to mention that the successful development of CBM in the US has laid an important technical foundation for the subsequent CBM development in other countries. Australia is another good example of the commercial development of CBM resources, but it had taken several years for achieving an obvious increase of CBM production. A substantial increase of CBM production occurred in 2015, boosting the annual CBM production to over 18 Bcm, subsequently, Australia surpassed the US as the leading CBM

✉ Jianhong Fu
fujianhong@126.com

✉ Bisheng Wu
wu046@mail.tsinghua.edu.cn

[1] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, Sichuan, China

[2] State Key Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China

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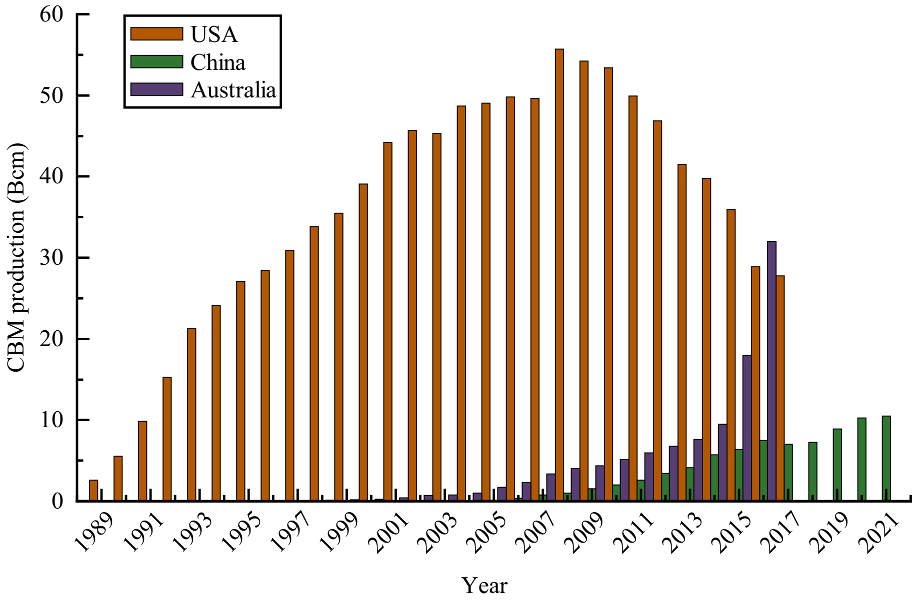


Fig. 1 Annual CBM production in the US, China and Australia, date from EIA (2022), National Bureau of Statistics (2022), Australian Government (2022)

producer in 2016 with the CBM production of 32 Bcm (Australian Government 2022). As for the CBM production in China, commercial-scale CBM production started in 2004 and did not see an increase until 2008. It has been increasing steadily in recent years, however, which is still significantly lower than that in the US and Australia, and it did not exceed 10 Bcm until 2020 (National Bureau of Statistics 2022).

In fact, CBM production has not increased significantly worldwide after nearly 30 years of commercial development, while the key factor that determines the production is absolutely the development, breakthrough and innovation of exploitation technologies. As we all know, the occurrence state of CBM is very special, most of which is primarily adsorbed on the surfaces of micropores in the coal matrix, only minor amounts are stored in large pores and fractures as free gas or solution gas in water (Rice 1993; Moore 2012; Flores 1998, 2013; Yang and Liu 2020). Moreover, the characteristics of CBM reservoirs vary in different regions around the world, such as coal structure, coal rank, gas content, permeability, reservoir pressure. Thus, CBM reservoirs show the unique properties that are different from other unconventional resources, this will cause a significant influence on everything about choosing and applying the optimal technologies during CBM exploration and exploitation, in which the efficient, safe and economic drilling and completion of CBM is an essential and critical process, but facing great challenges now (Shen et al. 2017; Tao et al. 2019; Yang and Liu 2019). Therefore, the development and prospect of drilling and completion technologies (DCTs) for CBM is a very important topic, which is worth discussing and summarizing. Throughout the development history of CBM DCTs in the world, it can be mainly divided into three technical patterns (Diamond and Oyler 1980; Flores 2013; Thakur 2016): (1) Underground CBM drainage by using the technology of drilling in-mine boreholes; (2) Draining or recovering CBM from coalbed by using the DCTs of surface vertical wells; (3) Extracting CBM by using the DCTs of surface directional or horizontal wells. Although drilling in-mine boreholes can also be considered as one kind of drilling technologies, the review focus of this paper are the surface DCTs of CBM.

It is worthwhile to mention here that the DCTs of CBM were developed based on those from the petroleum industry. Several milestones of CBM DCTs are summarized (Ayers 2002; Flores 2013; Shen et al. 2017; Tao et al. 2019): The fact that few CBM vertical exploratory wells drilled in Black Warrior and San Juan Basins in the early 1950s is the first milestone of CBM surface DCTs. The second milestone is related to the appearance of historic Amoco 1 Cahn vertical well that were drilled and completed in the San Juan Basin in 1977 to recover CBM from coalbed commercially. Since then, CBM was pronounced a viable commercial energy commodity. Stimulated by the enactment of the 'Crude Oil Windfall Profit Tax of 1980', CBM DCTs have evolved significantly with the rapidly increasing number of CBM wells (most are vertical wells) in the US. Benefited from the innovation of directional drilling technology and progresses in well completion technology, the success of drilling CBM horizontal wells from surface since late 1990s is another important milestone. Drilling from the surface is safer than from in-mine, and does not hinder mining. It should also be pointed out that although the cost of surface horizontal wells is higher than that of vertical wells, it has been proved that the CBM production from surface horizontal wells is more than several times that from vertical wells (Gentzis 2009; Wen et al. 2011). Therefore, the innovation and optimization of DCTs for horizontal wells gradually become the focus of CBM DCTs, so as to maximize the effectiveness of CBM production and economic viability.

Nowadays, the exploitation of CBM is still dominated by the mature DCTs of vertical wells, the CBM production is relatively low while comparing with other unconventional natural gas resources (such as the shale gas). The DCTs of CBM horizontal wells have been successfully applied and made some achievements, however, it is not yet comprehensively enough. Therefore, in the context of current energy transition and carbon neutral (Zou et al. 2021), CBM, as an important and clean natural gas resource, it is of vital importance to increase the exploitation efforts of CBM to meet the world's energy demands, this is inseparable from the development and innovation of CBM DCTs, among which the development of horizontal well technology is the top priority.

In order to review the CBM DCTs and its recent developments, Logan (1993) discussed the drilling techniques for CBM, Osisanya and Schaffitzel (1996) reviewed the horizontal drilling and completion techniques for recovery of CBM, Palmer (2010) discussed the role of permeability in choosing CBM completions, Shen et al. (2012) summarized the development of horizontal drilling technology for CBM in China, Ramaswamy (2008) and Caballero (2013) proposed the general selection methodology of drilling and completion techniques for CBM wells, Lau et al. (2017), Li et al. (2018) and Lu et al. (2021) compared the development status of CBM in China, the USA and Australia, and determined the engineering challenges and opportunities of CBM development in China, Tao et al. (2019) analyzed the current status and geological conditions for the applicability of CBM drilling technologies in China, Gao et al. (2022) reviewed the technical advances in well types and horizontal drilling and completion for high-efficient development of coalbed methane in China. It should be noted that, although some reviews on CBM DCTs have been made, they are very limited in number and scope. Meanwhile, some books, such as "Hydrocarbons from Coal" (Law and Rice 1993), "Coalbed Methane: Principles and Practice" (Rogers 1994), "Coalbed Methane Extraction" (Davidson et al. 1995), "Coal Bed Methane: From Prospect to Pipeline" (Thakur et al. 2014), "Coal and Coalbed Gas: Fueling and Future" (Flores 2013), "CBM Drilling and Completion Engineering Technology" (Shen et al. 2017), "Coal Bed Methane: Theory and Applications" (Thakur et al. 2020), contain only a small part of CBM DCTs or just the early historical development of CBM DCTs without involving its latest development. In other words, few researchers comprehensively reviewed the development of CBM DCTs. Therefore, a comprehensive overview is necessary for achieving a deeper understanding of CBM DCTs. The present overview updates the previous review papers or books and focuses on the CBM surface drilling and completion key technologies. Firstly, main well types for CBM exploration and its characteristics are summarized. Secondly, key technologies of CBM drilling, including directional drilling tool, measurement while drilling, geo-steering drilling, magnetic guidance drilling, underbalanced drilling, and drilling fluid are summarized and analyzed. Thirdly, CBM completion technologies such as open-hole, cavity and under-ream completion, cased-hole completion, screen pipe completion, and horizontal well completion are summarized and analyzed. Fourthly, achievements, challenges and prospects of CBM DCTs are discussed. Finally, a brief summary of CBM DCTs is presented.

2 Well types of CBM exploitation

Drilling operation is a necessary process for the and exploitation of CBM resources. Nowadays, there are a variety of CBM drilling technologies, each of which corresponds to a well type. In general, CBM well mainly includes three types, i.e., vertical well, cluster well and horizontal well. The cluster well and horizontal well belong to directional well. Moreover, the horizontal well can be further classified into several types, i.e., L-, U- and V-shaped well, ultrashort-radius well, and multilateral well.

2.1 Vertical well

A CBM vertical well refers to a well whose trajectory is a nearly plumb line from surface wellhead to underground target coal seam (Maricic et al. 2008; Tao et al. 2019), as shown in Fig. 2. Vertical drilling is the earliest, simplest and most widely used technology for the commercial development of CBM worldwide, and now it is still a main well type for CBM exploitation (Ayers 2002). Achieving rapid drilling, straightening and deflection prevention are the key technical requirements for drilling a CBM vertical well. The vertical drilling technology has been very mature, the technique is simple, drilling risk is small, and drilling cost of a single well is low. However, due to only a small contact area with the coal seam, the comprehensive benefit of CBM vertical well is not good, so hydraulic fracturing technology is usually required to increase CBM production from vertical wells (Colmenares and Zoback 2007). In situations where there are numerous, thin coal seams with reasonable permeability (5–10 mD), vertical drilling and completion are the preferred option (Gentzis 2009).

2.2 Cluster well

Affected by the complex terrain and surface conditions, such as in the mountainous and hilly areas, there is only

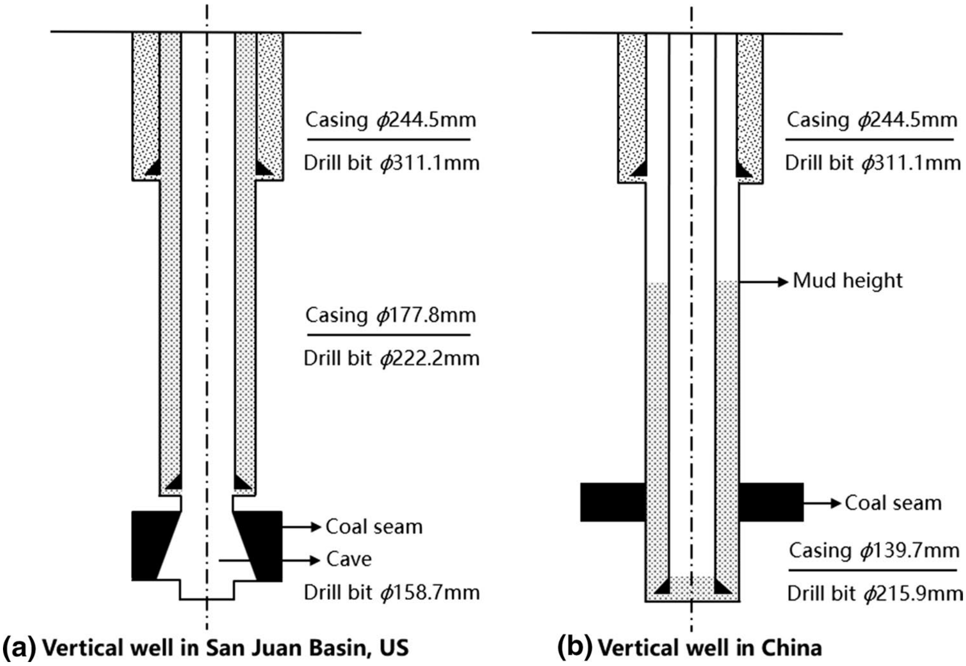


Fig. 2 Schematic of the wellbore structure of CBM vertical wells, modified from Shen et al. (2017)

less flat surface suitable for drilling CBM wells, which cause high difficulty in deploying a large-scale development well pattern. Therefore, the cluster well was frequently used for CBM exploitation of these CBM reservoirs (Zhu et al. 2015; Wen et al. 2019; Tao et al. 2019). Cluster well is usually composed of several directional wells, which are drilled in different azimuths from the same limited well site, and each well can reach the target coal seam along its designed wellbore trajectory (Shen et al. 2017). Accurate control of drilling trajectory and efficient prevention of collision of wells are two key aspects while drilling the cluster well. There are generally four to nine directional wells in a cluster well platform, and the wellhead spacing is about 4–6 m, as shown in Fig. 3.

Compared with the single vertical well development pattern, the cluster well has several obvious advantages (Tao et al. 2019). Firstly, from the perspective of land acquisition and environmental protection, the cluster well covers a small surface area and has a less damage to the environment. Secondly, the cost of surface technological processes of cluster well is lower, and it is more convenient for later production centralized management. Moreover, the deployment of

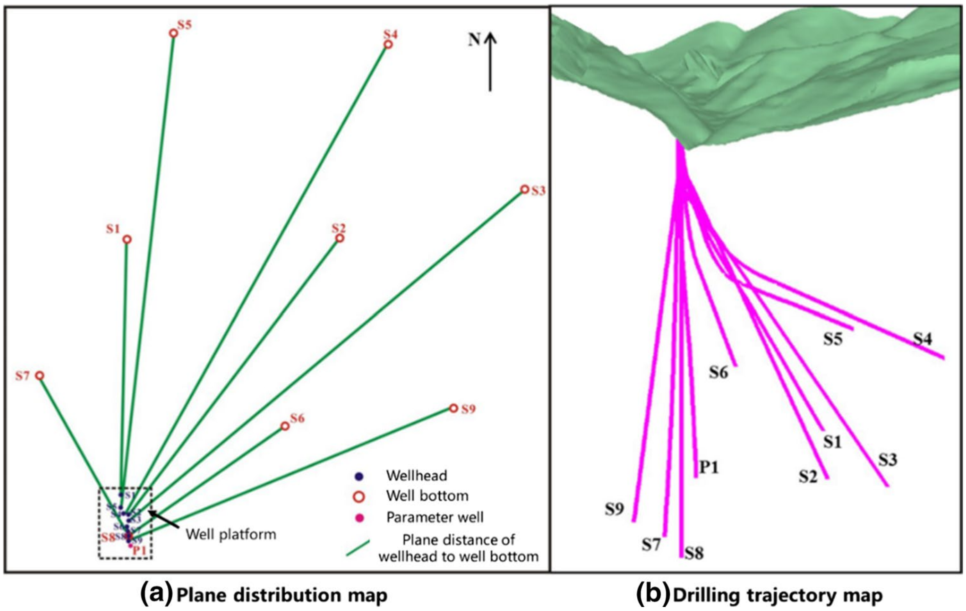


Fig. 3 Schematic of deployment of the cluster well in the Songhe area, Guizhou Province, China (Tang et al. 2017)

cluster well is also beneficial to the implementation of the "well-factory" drilling pattern, with drilling, completion, and stimulation performed on one platform. This greatly simplifies the drilling operation, improves equipment utilization, and reduces the costs of drilling fluid and effectively shortens the drilling cycle. The exploration and development practices have proven that this type of well has achieved good effects in many regions of China, such as YCN and Songhe areas (Tang et al. 2017; Gao et al. 2022). Thus, the cluster well has a vital significance for achieving the low-cost development of CBM.

2.3 Horizontal well

In order to drill a CBM horizontal well, a vertical wellbore is firstly drilled from the surface to an underground location directly above the target CBM reservoir called the "kickoff point", then the directional drilling tool is used to deviate the wellbore trajectory from the vertical plane and entry into the reservoir at the "landing point" with a near-horizontal inclination, and the well continues to extend in the reservoir horizontally until it reaches the expected bottom hole position, as shown in Fig. 4. The angle-build rate and turn radius are usually used for classification of different horizontal wells, as listed in Table 1 (Joshi 1987; Short 1993; Flores 2013; Ma et al. 2016), and most of horizontal wells are drilled within the parameter ranges in Table 1 because of equipment limitations. Since the first CBM horizontal well was drilled from the surface by the Bureau of Mines in 1978 in Southwestern Pennsylvania (Diamond and Oyler 1980), based on the horizontal drilling technologies from the petroleum industry, CBM horizontal drilling technology has been continuously optimized, innovated and developed. Currently, L-, U-, V-shaped, ultra-short radius and multilateral horizontal well have been successfully applied to CBM exploitation, and all of them are usually effective in facilitating drainage, pressure reduction and gas extraction (Shen et al. 2017; Tao et al. 2019; Yang et al. 2019b; Zhao and Yi 2020; Gao et al. 2022).

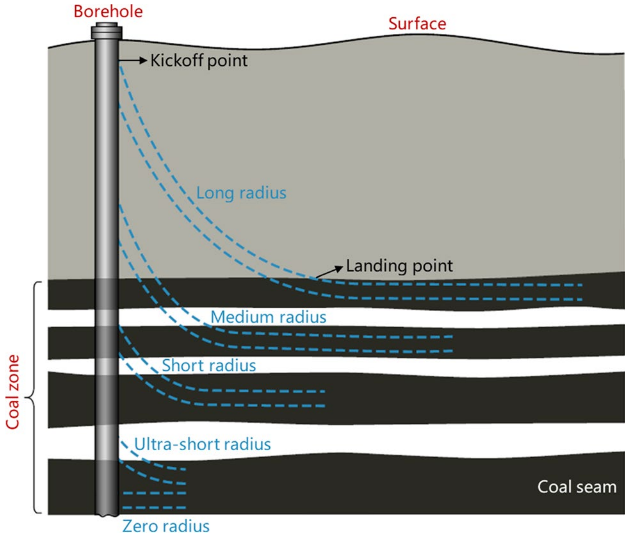


Fig. 4 Schematic of CBM horizontal well with different turn radius, modified from Flores (2013)

2.3.1 L-shaped horizontal well

CBM L-shaped horizontal well is the simplest type of horizontal well from the perspective of wellbore trajectory design, with the maximum well inclination angle of approximately 90° and horizontal or near horizontal segment in the target coal seam (Tao et al. 2019). According to the occurrence of the landing coal seam, the wellbore trajectory of L-shaped well can be adjusted and usually divided into two types of horizontal segment up-dip and down-dip, as shown in the Fig. 5.

L-shaped well has only one main borehole, the screen pipe or casing can be run into the whole horizontal segment to obtain a stable wellbore, which can be reentered, maintained and operated in the late production stage, and staged hydraulic fracturing, nitrogen unclogging or sectional cavity creating can be conducted to improve CBM production (Zhu et al. 2018; Zhao and Yi 2020). L-shaped well is more suitable for the "well factory" pattern of CMB horizontal

Table 1 Classification of the horizontal well, after Flores (2013) and Ma et al. (2016)

Radius type	Zero	Ultra-short	Short	Medium	Long
Turn radius (ft)	0	1–2	20–40	300–800	1000–3000
Build rate	–	–	100–300 (°/100 ft)	6–20 (°/100 ft)	2–6 (°/100 ft)
Achievable horizontal distance (ft)	10	100	300–800	1000–3000	2000–5000
Devices and operation	Special	Special	Special	Approximate conventional	Conventional
Trajectory survey	Telescopic probe	Coiled tubing	Oil-pipe	MWD	MWD
Controlled method	–	Special turning system	Whipstock or PDM tool	PDM tool	PDM tool
Cost	High	High	Medium	Low	Low

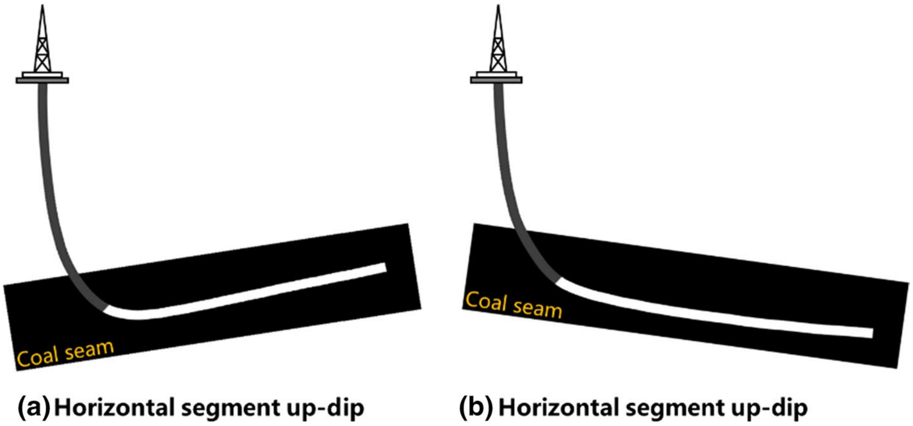


Fig. 5 Schematic of CBM L-shaped horizontal well, modified from Tao et al. (2019)

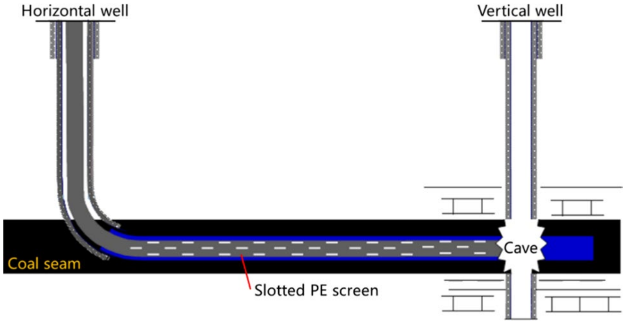


Fig. 6 Schematic of CBM U-shaped horizontal well (Zhang et al. 2013)

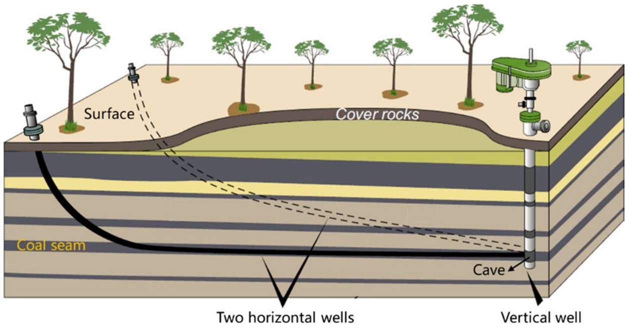


Fig. 7 Schematic of CBM V-shaped horizontal well, modified from Flores (2013)

well (Gao et al. 2022). However, L-shaped well has a high requirement for wellbore trajectory control, and it is usually difficult to achieve one-time "soft landing" and ultra-long horizontal segment footage (Shen et al. 2017). In addition, the rodless drainage technology is not yet mature, thereby, drainage equipment and method are another key restriction for the promotion and application of this type of well (Zhao and Yi 2020).

2.3.2 U/V-shaped horizontal well

CBM U-shaped horizontal well has integrated multiple advanced technologies such as horizontal well technology, cave building technology, intersection technology of two wells, underbalanced drilling and geo-steering technology (Zhao et al. 2011; Zhang et al. 2013; Tao et al. 2019). A CBM U-shaped horizontal well usually consists of one or more horizontal wells and one vertical well, which are intersected in the cave, as shown in Fig. 6. Thus, U-shaped well is available for extracting CBM from multiple coal seams.

Compared with the vertical well and L-shaped well, U-shaped well has the advantages of larger single well production and recovery rate, but the technical requirements and cost are higher. Moreover, while comparing with the multilateral well, U-shaped well has the following advantages: the shorter drilling cycle and less risk because of no need for sidetracking branches; the entire horizontal segment can be completed with polyethylene (PE) screen pipes, which is beneficial to prevent wellbore collapse, and the PE screens can also be used for intermittent well washing operations in the production stage to ensure the smooth flow of CBM (Zhao et al. 2014; Zhao and Yi 2020); the borehole can be reentered, maintained and operated in the late production stage (Liu et al. 2015); for coal seams with ultra-low permeability, the staged fracturing operation is also available in U-shaped well (Gokdemir et al. 2013; Shen et al. 2017).

In addition, when two U-shaped horizontal wells share the same vertical production well and there is a certain angle between them, it is so called as the V-shaped horizontal well (Flores 2013; Shen et al. 2017; Tao et al. 2019), as shown in Fig. 7. In this condition, the water and gas are able to flow into the same vertical wellbore from two different horizontal boreholes, thereby increasing the drainage area, reducing the drilling cost and improving the CBM production while retaining the advantages of U-shaped well. Moreover, some extra advanced techniques such as three-well docking and multi-borehole completion are also integrated in V-shaped well. V-shaped well may be the most efficient and suitable type of horizontal well for CBM exploitation present (Zhao and Yi 2020).

2.3.3 Ultrashort-radius horizontal well

Ultrashort-radius horizontal well refers to a horizontal well whose curvature radius is shorter than the conventional short curvature radius, the applied drilling system is called as Ultrashort-Radius Radial System (URRS) (Dickinson et al. 1989; Marbun et al. 2011), as shown in Fig. 8. The most important component of URRS may be the steering system, which can control the wellbore trajectory to turn from vertical to horizontal with an ultrashort-curvature radius (about 0.3 m), and enter into the coal seam through the open-window on casing (Xian et al. 2010). The high-pressure fluid is transported in jetting hose to provide power for the hydraulic jet rock-breaking bit, which is able to drill a radial horizontal borehole. Compared to conventional horizontal drilling, URRS avoids the frequent operations of deflecting and orientating and complicated control of wellbore trajectory. Moreover, the use of self-propelling rotary jet bit has no need for applying WOB and rotating drill-string, which is beneficial to improve the rock-breaking efficiency, form regular and long boreholes, and reduce the occurrence of downhole accidents (Li et al. 2017a). Furthermore, it is feasible to use URRS to drill radial horizontal boreholes in multiple coal seams, so as to improve development efficiency, as shown in Fig. 9. Due to the small borehole diameter, ultrashort-radius horizontal well is more suitable for coal seams with high permeability, relatively stable structure, and high gas content and saturation (Shen et al. 2017).

In addition, in order to solve problems, such as the large window and curvature radius in conventional sidetrack drilling, small drilling bit in radial horizontal well with hydraulic jetting, and short drilling footage in coal seam, T-shaped horizontal drilling technology has been developed (Yang et al. 2018) by using the flexible drilling tool assembly composed of drill pipes with the single length of 0.15 m and flexible short sub to transmit WOB and TOB, as shown in Fig. 10. Its side opening window is small with only about 20 cm in size, which causes less damage to the casing, and its curvature radius can be controlled within 3 m, which can make the near-well CBM resources fully exploited.

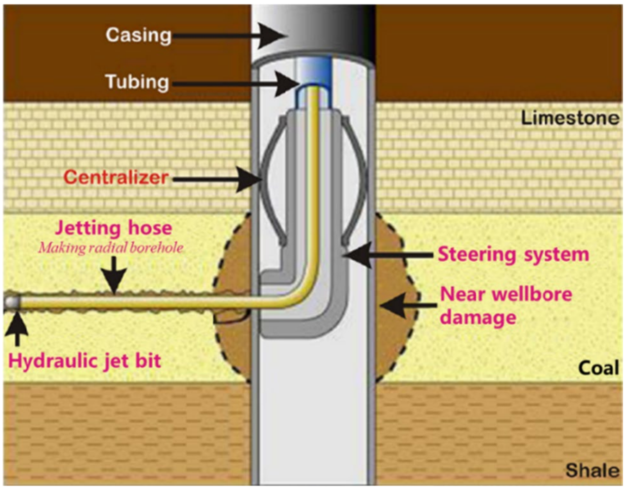


Fig. 8 Schematic of URRS, after Marbun et al. (2011)

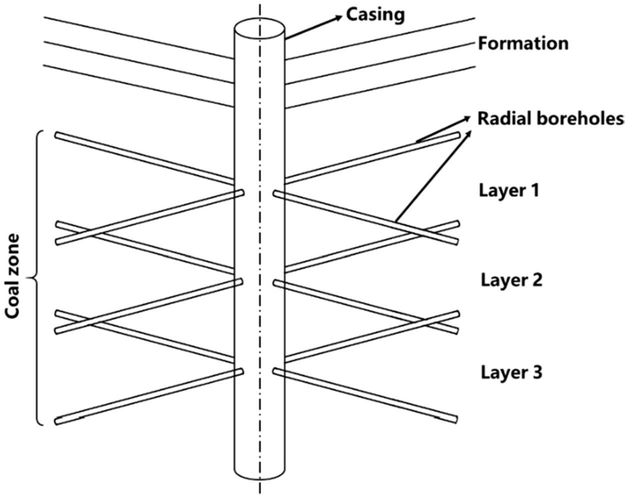


Fig. 9 Schematic of radial boreholes in multiple coal seams, after Dickinson et al. (1989)

2.3.4 Multilateral horizontal well

The CBM multilateral horizontal well can be single-lateral, dual-lateral, trilateral, quadrilateral and pinnate (Maricic et al. 2008), as shown in Fig. 11. Nowadays, the pinnate horizontal well, also known as fishbone-shaped horizontal well, may be the most commonly used one. Figure 12 shows a pattern of pinnate wells (Palmer 2010). The single pinnate well, which is taken as an example to explain its principle, usually consists of a vertical well with a cave in the coal seam, a horizontal well with one or two main boreholes and multiple branched boreholes, and the wells are intersected in the cave, as shown in Fig. 13. The main borehole is drilled through the cave and then extends in the coal seam with a long distance. Multiple branched boreholes are drilled from different positions on both sides of the main borehole by using sidetracking technology. The branched boreholes can maximally cross and communicate natural fractures and cleat systems in the coal seam so that the conductivity capacity is much better and gas drainage area is much larger than other types of horizontal wells (Gentzis and Bolen 2008; Tao et al. 2019).

In general, CBM multilateral well has the advantages of high production, approximately 5 to 10 times higher than

Fig. 10 Schematic of T-shaped horizontal well and flexible drilling tools, modified from (Yang et al. 2018)

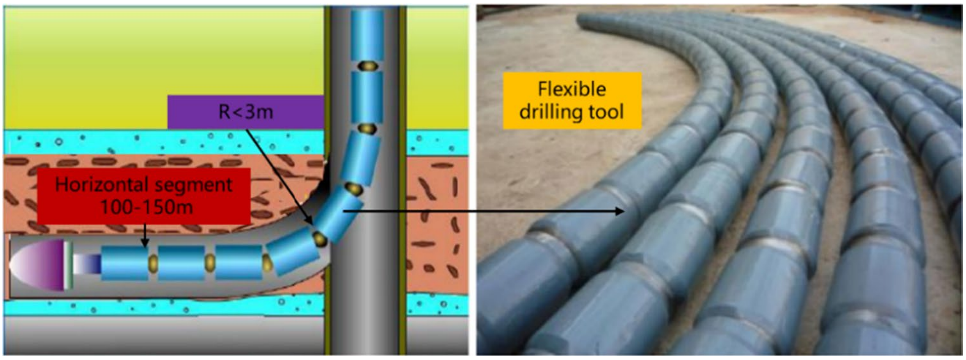
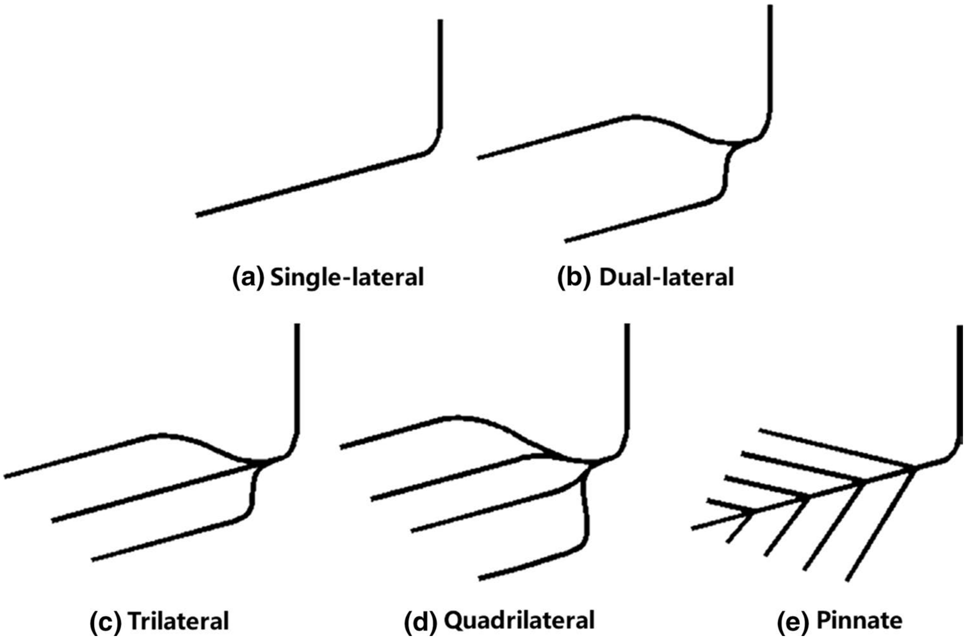
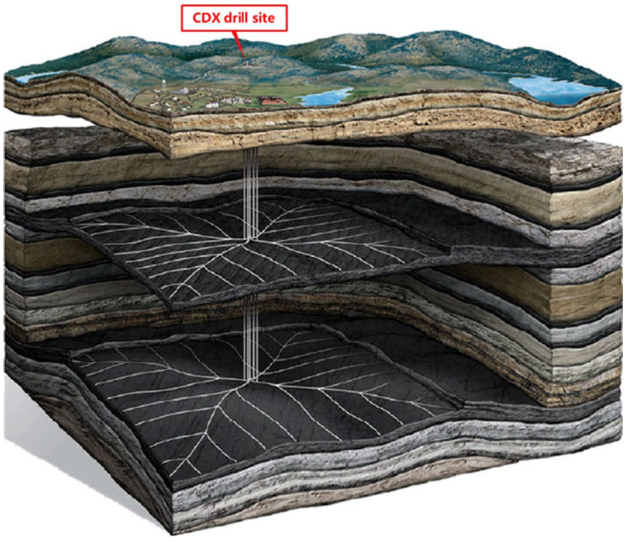


Fig. 11 Different patterns of multilateral well (Maricic et al. 2008)





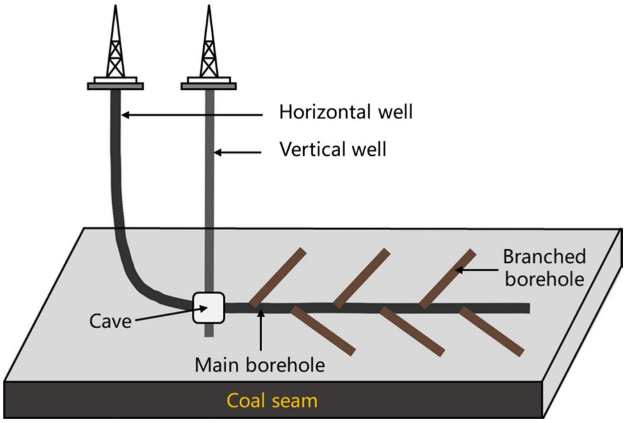


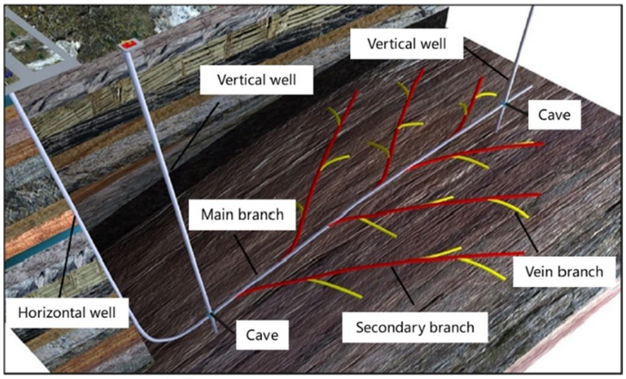
Fig. 13 Schematic of a single pinnate horizontal well, after Tao et al. (2019)

Fig. 12 Pinnate pattern of multilateral wells by CDX (Palmer 2010) that of a vertical well with hydraulic fracturing, greatly shortening the production cycle, good economic benefits, small wellsite area and low damage to the environment (Tabatabaei and Ghalambor 2011; Duan et al. 2012). However, due to the extremely complex drilling operations and high maintenance difficulty, the problems such as high drilling cost, poor wellbore stability, difficult in monitoring, re-entering and flushing the borehole, short production life, and less available enhancement measures are also obvious (Gentzis and Bolen 2008; Ren et al. 2014; Zhu et al. 2015; Zhang et al. 2017b). Therefore, CBM multilateral well is usually suitable for CBM reservoirs with developed fractures, moderate coal seam thickness and depth, simple and complete coal structure, low permeability, high mechanical strength, good coal seam stability, high gas content and saturation, or the presence of many thin coal seams (Ramaswamy 2008; Shen et al. 2017; Gao et al. 2022).

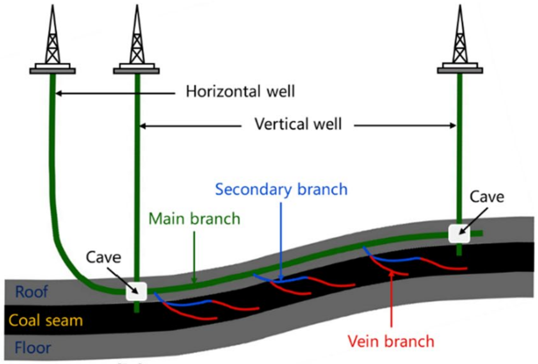
In order to solve the problems related to serious collapse of coal seam, footage failed to meet the design requirement, difficult in monitoring, re-entering and flushing the boreholes that occur in the multilateral well, the tree-like horizontal well is innovatively proposed based on the idea of "main branch to provide a passageway, secondary branch to control the gas production area, and small branch to increase the output" (Yang et al. 2014). The tree-like well usually consists of one horizontal well and two vertical wells, as shown in Fig. 14. The main branch is drilled on the stable roof or floor of the coal bed and intersected with the vertical wells in the caves, the secondary branches are sidetracked from the main branch into the coal seam, and small branches are drilled from the secondary branches.

Compared with the conventional pinnate well, the biggest advantage of the tree-like well is that the stability of the main branch is much better, and it can be monitored, re-entered and flushed, while the disadvantage is that the drilling cost is higher, drilling circle is longer, and the requirements for roof/floor stability and geological conditions of coal bed are much higher (Yang et al. 2014).

Based on the above introduction of different well types for CBM exploitation, a detailed comparison of these well types are summarized in Table 2. Moreover, according to the research work by Tao et al. (2019), the coal structure, vitrinite reflectance (R_o), in situ stress, and the ratio of critical desorption pressure to the reservoir pressure ($R_{c/r}$) were considered as the main parameters to proposed a set of optimization methods for well type selection, which could be potentially beneficial for improving the applicability of CBM horizontal wells to geological conditions, as shown in Fig. 15. Furthermore, some achievements that have been achieved in CBM drilling of different well types are listed in Table 3. In general, cluster well has a better applicability to different geological conditions and shows favorable application effects; L-, U-, V- shaped wells are now also widely used and can be applied to high-rank CBM reservoirs with low permeability and deep CBM reservoirs with high in situ stress, however, the reservoirs should have a relatively intact coal structure; ultrashort-radius well have been applied for limited regions in China and Australia (Gao et al. 2022); multilateral well is probably the most efficient technology for CBM exploitation, but it is greatly affected by coal seam characteristics, in situ stress conditions and other factors, resulting in its applicability for complex geological conditions required to be further improved, especially in high-rank coal seams and in deep coal seams with high in situ stress (Tao et al. 2019).



(a) Cross-section diagram



(b) Tree-like roof horizontal well

Fig. 14 Schematic of the tree-like horizontal well, modified from Yang et al. (2014) and Tao et al. (2019)

3 Key technologies of CBM drilling

3.1 Directional drilling tool

In order to realize the successful application of various complex well types mentioned above for CBM exploitation, it is indispensable to use the advanced drilling tools and equipment. Conventional downhole equipment for CBM drilling includes the drill pipe, heavy weight drill pipe, drill collar, non-magnetic drill collar, substitute sub, stabilizer and

Table 2 Comparison of different CBM well types, after Shen et al. 2017 and Tao et al. 2019

Type	Subtype	Geological adaptation	Well site requirement	Control area of a single well	Cost per well ($\times 10^4$ USD)	Wellbore stability	Alteration ability	Maintainability
Vertical well	Vertical	Poor-adapted	Strict	Small (< 0.1 km^2)	Low	Good	Yes	Simple
Cluster well	Directional	Well-adapted	Simple	Large (0.4–0.7 km^2)	Relatively low	Relatively good	No	Medium
Horizontal well	L-shaped	Well-adapted	Simple	Approximate medium (0.1–0.3 km^2)	Approximate medium (~ 50)	Relatively good	Yes	Simple
	U-shaped	Well-adapted	Relatively strict	Medium (0.1–0.3 km^2)	Medium (~ 95)	Relatively good	Yes	Relatively simple
	V-shaped	Well-adapted	Relatively strict	Relatively large (0.2–0.6 km^2)	Medium (~ 95)	Relatively good	Yes	Relatively simple
	Ultra-short radius	Poor-adapted	Relatively simple	Relatively large	Medium	Medium	No	Medium
	Multilateral	Poor-adapted	Strict	Large (0.4–0.7 km^2)	High (~ 150)	Poor	Hard	Difficult
	Tree-like	Poor-adapted	Strict	Large (0.5–0.8 km^2)	High	Relatively good	No	Difficult

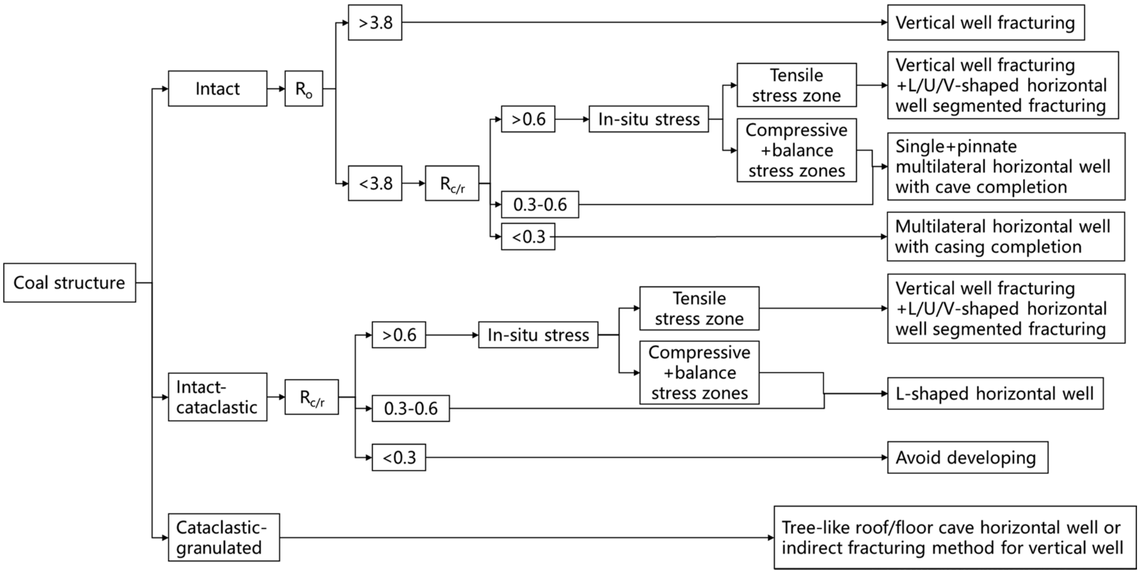


Fig. 15 Flow chart of CBM well type optimization technology, after Tao et al. (2019)

centralizer. Moreover, for ensuring an accurate, efficient, economic and safe CBM directional or horizontal drilling, specialized directional tools are required to be used to help engineers complete the directional drilling operation, the most commonly used of which is positive displacement motor (PDM) tools, while the rotary steerable drilling system (RSDS) with much better directional effect that has been widely used in shale gas development has not been used in CBM drilling, mainly because the restriction of low-cost requirement for CBM exploitation. However, when the tool costs are significantly reduced in the future, for its absolute technical advantages, RSDS may be widely applied in complex drilling operations of CBM, such as the distant intersection of two wells, sidetrack drilling of branched boreholes, which all pose an extremely high requirement for steering and positioning accuracy (Tao et al. 2019; Qiao et al. 2021).

Table 3 Some drilling achievements of several typical CBM well types

Type	Subtype	Well	Burial depth (m)	Achievements	Source
Vertical well	Vertical	Amoco 1 Cahn	-	First commercial vertical well	Ayers (2002)
Cluster well	Directional	S1-S9	500.58–771.62	9 directional wells	Tang et al. (2017)
Horizontal well	L-shaped	ZP02-1 N	-	Footage in coal seam with 1000 m	Shen et al. (2017)
	U/V-shaped	FSU2H	-	Distant intersection with 993.27 m Very short drilling cycles with 28 d	Shen et al. (2017)
	Ultra-short radius	FS-1	819–965	15 radial boreholes Total footage in coal seam with 2941 m Single-borehole maximal footage with 201.4 m	Shen et al. (2017)
	Multilateral	WM1-1	900 m	2 main branches 10 secondary branches Total footage with 7993 m	Shen et al. (2017)
	Tree-like	QS12P1H	600 m	1 main branch 15 secondary branches 33 vein branches Single-well total footage with 13270 m and pure coal footage with 10,288 m	Ran et al. (2021)

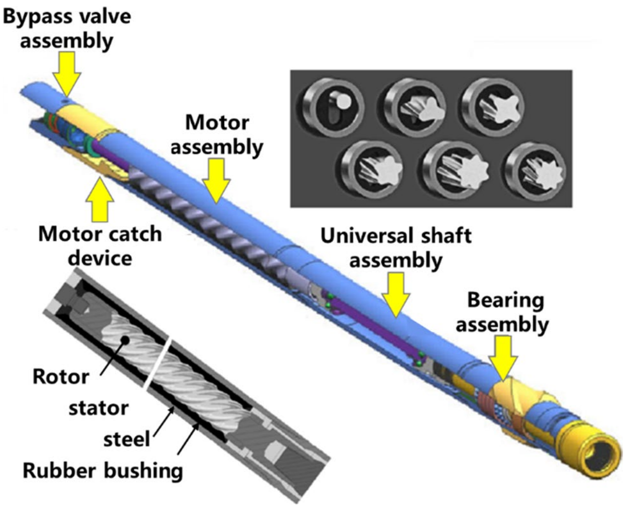


Fig. 16 Schematic of a typical PDM tool (Ma et al. 2016)

3.1.1 Typical PDM tool

A typical PDM tool usually consists of four components, i.e., bypass valve assembly, motor assembly, universal shaft assembly and bearing assembly (Ma et al. 2016), as shown in Fig. 16. The main function of bypass valve assembly is to control the working state of the motor, which is prevented from rotating when the tool is drilling into the hole or pulling out of the hole. The core components of motor assembly include the stator and rotor. The universal shaft assembly transmits the rotating speed and torque generated by the motor to the drive shaft, while compensating for the eccentric movement of the rotor vibration and absorbing its downward thrust. Since the operating life of the PDM tool is usually determined by the durability of the bearings, the bearing assembly is probably the most important component. The bearing assembly can transmit the rotating power to the drill bit, and maintain the central position of the drive shaft to ensure smooth rotation, while bearing the axial and radial loads generated by the WOB.

3.1.2 PDM tool with the bent housing

PDM tool with the bent housing is developed based on the PDM tool with the orientation sub and bent sub (Ma et al. 2016). Currently, PDM tool with the single bent housing is the most commonly used one in CBM directional drilling, as shown in Fig. 17. The bent housing is a special deflecting device that is usually installed between the motor and bearing assembly, which can achieve a slight bend of 0°–3° with approximately six increments in deviation per degree of bend (Ma et al. 2016). Compared with the bent sub PDM, bent housing PDM is more practical and efficient in directional drilling operation. At present, combining the bent housing PDM with MWD, a conventional CBM directional or horizontal drilling can be realized, while the simple CBM geo-steering drilling can be accomplished by combining it with LWD.

3.2 Measurement while drilling

In order to realize accurate control of wellbore trajectory during CBM directional drilling, measurement while drilling (MWD) is indispensable by carrying out real-time measurement of downhole information by using the sensors located in the down-hole assembly adjacent to the drill bit during

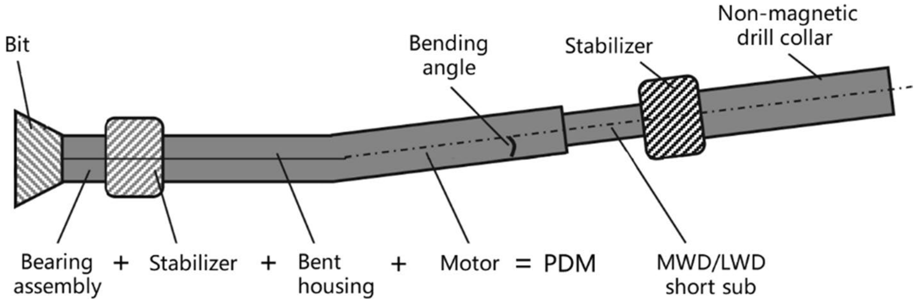


Fig. 17 Schematic of drill tool assembly with the single bent housing PDM

drilling, and these measurements can be recorded in downhole and/or transmitted to surface.

3.2.1 Measuring technology

Conventional MWD tools are usually able to measure the directional information such as the inclination, azimuth and tool face in real time, thereby, the wellbore trajectory and bit location can be calculated (Wu et al. 2012; Ma and Chen 2015). Moreover, by adding special separate subs/tools on MWD tools, obtaining the drilling engineering information such as down-hole pressure, WOB, TOB, temperature and rotation speed, as well as measuring the formation information such as natural gamma and resistivity (so called as logging while drilling) are also available (Ma and Chen 2015; Liu et al. 2018; Ma et al. 2018a, 2020b). The drilling engineering information is helpful for identifying the down-hole conditions and the working status of drilling tools, while the formation information is mainly used for CBM geo-steering drilling.

3.2.2 Transmission technology

According to the difference of transmission medium, the technology for downhole data transmission can be divided into four types: mud pulse telemetry, electromagnetic telemetry, acoustic wave and wired drill pipe. Table 4 compares the performance of these transmission technologies. At present, only mud pulse telemetry and electromagnetic telemetry are commonly used in CBM directional drilling.

(1) Mud pulse telemetry

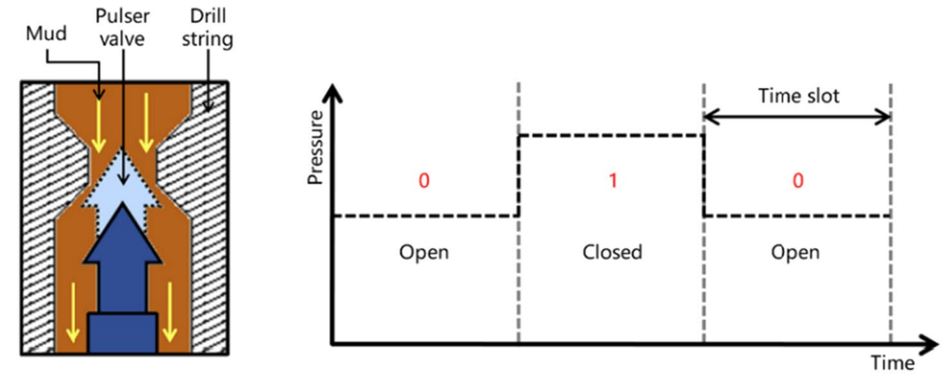
Mud pulse telemetry (MPT) is the most common method for data transmission used by MWD tools. MPT transmits the measured downhole data to surface by means of coded pressure pulses (or fluctuations) via the channel formed by drilling fluid that flows inside the drill-string (Klotz et al. 2008a, b; Mwachaka et al. 2019; Li et al. 2022a). Usually, a mud pulser, mud siren or oscillating shear valve can be utilized to restrict the flow of drilling fluid to generate pressure pulses in downhole (Hutin et al. 2001; Klotz et al. 2008a; Caruzo et al. 2012). Three kinds of MPT methods, including positive-pulse, negative-pulse and continuous wave, are shown in Fig. 18. Specific principles of these three methods can refer to the literatures (Hutin et al. 2001; Caruzo et al. 2012; Berro and Reich 2019). In general, MPT has the advantages of better stability, lower costs, reliable data transmission, and simple implementation, while the disadvantages of lower transmitting rates and strict requirements for drilling fluid also exist.

(2) Electromagnetic telemetry

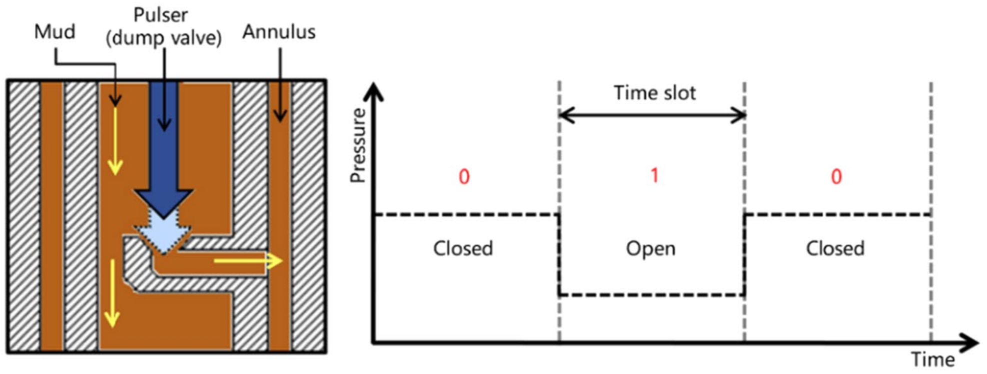
The electromagnetic telemetry, also called as EM-MWD, consists of three parts, i.e., the downhole electromagnetic transmitter device installed in the non-magnetic drill collar,

Table 4 Performance of different MWD technologies, after Ma et al. (2016) and Mwachaka et al. (2019)

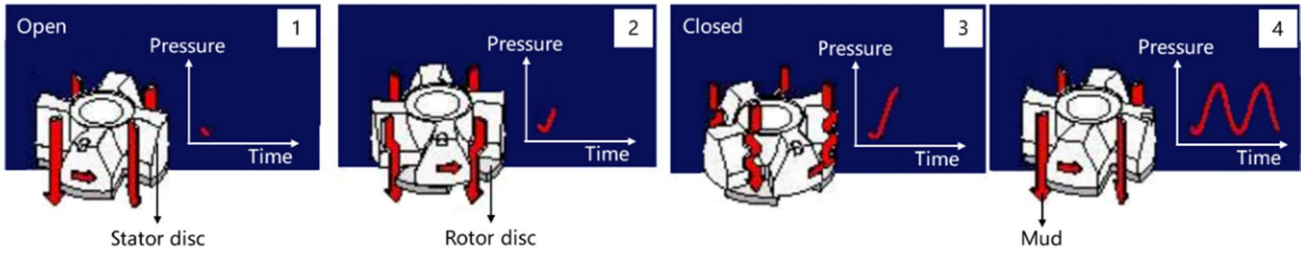
Transmission technologies	Subtype	Depth (m)	Date (bit/s)	Reliability	Data quantity	Signal attenuation	Signal interference	Cost
Mud pulse telemetry	Positive-pulse	> 6000	< 3	Good	High	Medium	Medium	Low
	Negative-pulse	> 6000	< 3	Good	High	Medium	Medium	Low
	Continuous wave	> 6000	< 18	Good	High	Medium	Medium	Medium
Electromagnetic telemetry	EM-MWD	600–6000	< 400	Bad	Medium	High	High	Medium
Acoustic wave	N/A	1000–4000	100	Bad	Low	High	Medium	Medium
Wired drill pipe	N/A	> 6000	1–2 M	Bad	Very high	N/A	Low	High



(a) **Positive pulser for generating discrete pressure pulses**



(b) **Negative pulser for generating discrete pressure pulses**



(c) **Mud siren for generating continuous pressure waves**

Fig. 18 Three kinds of mud pulse telemetry methods (Caruzo et al. 2012; Berro and Reich 2019)

the directional measuring probe located at the lower end of the drill string to continuously monitor various downhole information, and the surface receiver (Ma et al. 2016; Liu 2020), as shown in Fig. 19. The downhole electromagnetic transmitter is used to generate electromagnetic signals, which can propagate through the formation to the surface where they are received by the surface antenna and then transmitted to the processing center and decoded into measurements. The advantages of EM-MWD includes no need for drilling fluid circulation, high transmission rates, two-way communication between the surface and downhole. Moreover, EM-MWD is able to operate in conditions that the mud pulse telemetry is not applicable, such as the air, foam and aerated underbalanced CBM drilling.

3.3 Geo-steering technology

Geo-steering technology plays a significant role in CBM horizontal drilling, especially the multilateral horizontal well (Meszaros 2007; Shen et al. 2016; Gao et al. 2022). Through the real-time comprehensive analysis of engineering parameters, geological parameters and mud logging parameters that are measured by logging while drilling (LWD) and mud logging unit near the drill bit, the engineers are able to adjust the wellbore trajectory in time, and control the directional drilling tool to accurately land at the target location and then keep directionally extending within the coal seam, so as to ensure a smooth drilling

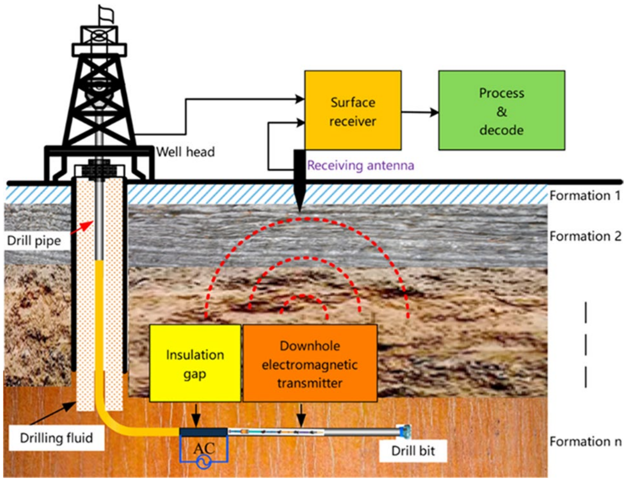


Fig. 19 Schematic of electromagnetic telemetry, after Liu (2020)

process and guarantee the probability of encountering coal seams while drilling.

3.3.1 Logging while drilling

LWD is a key component of geo-steering technology, which was developed on the basis of traditional wire-line logging techniques (Li et al. 2005; Wu et al. 2012; Ma et al. 2016). Making a real-time measurement of formation characteristics is the main function of LWD tools, such as gamma ray, resistivity, caliper, acoustic wave, density, neutron porosity and formation pressure, thereby, formation evaluation, drilling optimizing and geo-steering can be achieved. However, restricted by the requirement of low-cost development of CBM, only gamma ray and resistivity LWD are frequently used in CBM geo-steering drilling now.

(1) Gamma ray logging while drilling

Gamma ray LWD is usually composed of the downhole gamma probe and surface data processing system. The gamma probe is connected at the lower end of the measuring probe of MWD, which can detect the gamma ray intensity of different rocks in the coal seam, convert and store them into gamma measurements. The measurements are then transmitted to the surface through the mud pulse or electromagnetic signals, so that to obtain the real-time gamma curve of the coal seam. The gamma curve is used to divide lithology and compare strata, so as to determine the drill bit position, adjust the wellbore trajectory in time, and achieve geo-steering drilling. In order to obtain more accurate results, two or more gamma detectors are usually used to simultaneously measure gamma data from different orientations, this is so called focused gamma or azimuthal gamma LWD, which are now commonly used in CBM geo-steering drilling (Wheeler et al. 2012; Thwait and Suh 2014; Qin et al. 2021; Gao et al. 2022).

(2) Resistivity logging while drilling

The resistivity LWD is usually divided into two categories: lateral resistivity and induction resistivity (Wu et al. 2012). Induction resistivity LWD is widely used in CBM drilling, which adopts the measurement principle of array compensation electromagnetic wave propagation resistivity. The coal seam resistivity is characterized by comparing the phase shift and amplitude decay amplitude of voltage oscillating sine waves of two frequencies received by two receivers (Zhao 2017). However, resistivity LWD is usually affected by environmental factors such as the thickness of coal seam, the resistivity of surrounding rocks, rock anisotropy, mud intrusion, and instrument eccentricity. Therefore, resistivity inversion is required to be conducted to obtain more useful coal seam information such as true formation resistivity, invasion radius, horizontal and vertical resistivity.

3.3.2 Geo-steering drilling of CBM horizontal well

Using geo-steering technology to conduct the drilling of CBM horizontal well usually includes the following four procedures, as shown Fig. 20 (Meszaros 2007; Wheeler et al. 2012; Shen et al. 2017; Gao et al. 2022): (1) Geological data collection and analysis before drilling: collecting geological data of target area, combining logging and seismic data of adjacent wells, analyzing coal seam characteristics, dividing target coal seam in detail, selecting marker layers, predicting coal seam depth, and establishing geological model. (2) Geological design and drilling engineering design before drilling: according to the characteristics of target coal seam, designing wellbore trajectory, and selecting suitable drilling methods, drilling tools and supporting geo-steering methods. (3) Real-time geo-steering drilling: modifying and updating the geological model in real time by comparing with the measured data of MWD, LWD and mud logging unit, called as simulation-comparison-model update method, thereby, the drill bit location can be confirmed and the wellbore trajectory can be adjusted in time. (4) Summary and analysis after drilling: updating the geological model, and providing a basis for subsequent geo-steering operations in this block.

In actual horizontal drilling process, as the target coal seam may be up-dipped or down-dipped, and interlayers or faults may exist, the real wellbore trajectory usually cannot extend along the trajectory designed before drilling, and the drill bit may drill out of the target coal seam. In order to solve these problems, it is necessary to accurately calculate the inclination, apparent dip angle and thickness of the target coal seam, and identify the position and direction of the drill

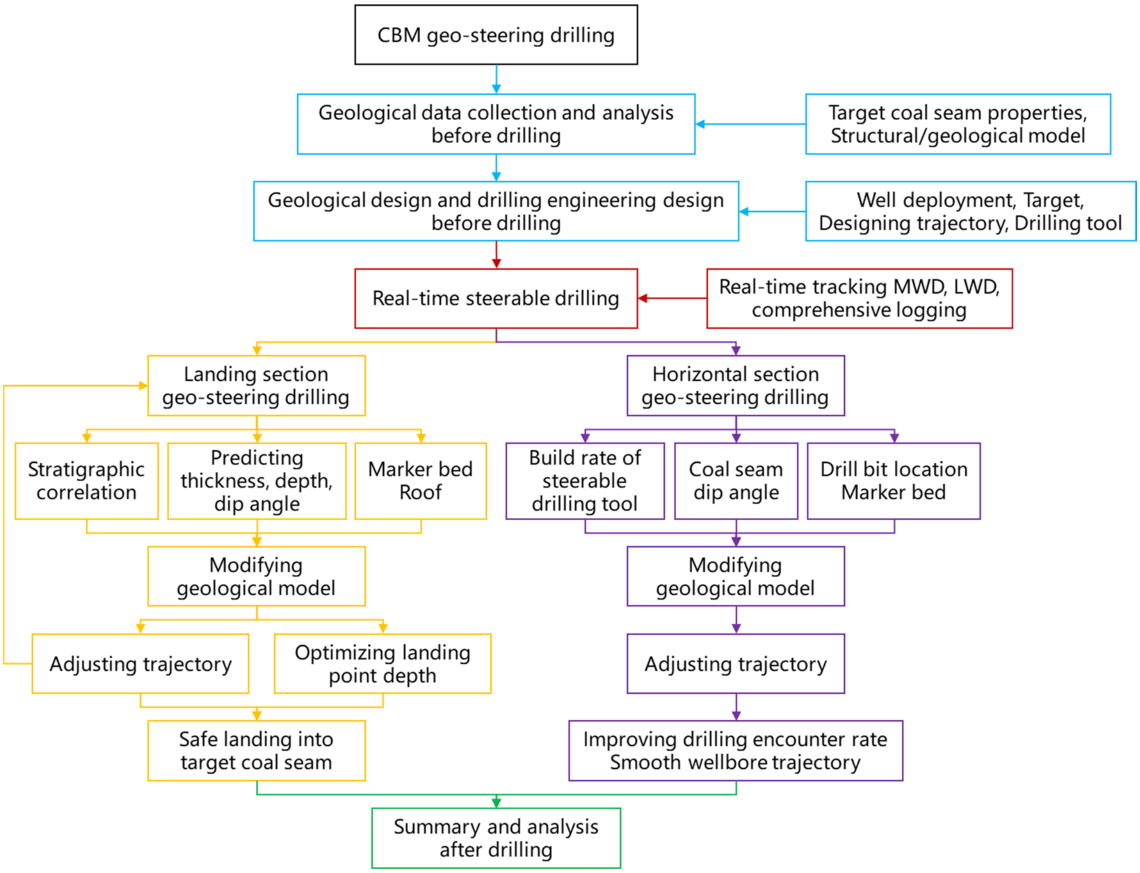


Fig. 20 Flow chart of geo-steering drilling for CBM horizontal well

bit in real time. Moreover, for thin and multiple coal seams, high and steep structure coal seam, or other coal seams with complex geological structures, conventional geo-steering usually cannot meet the accuracy requirements of wellbore trajectory control, so near-bit geo-steering technology is required to be used (Chen et al. 2019a; Gao et al. 2022).

(1) Calculating the coal seam dip angle. Both the resistivity and azimuthal gamma LWD can be used to calculate the dip angle. In addition, using the vertical depth that the drill bit drills into and out of the coal seam to calculate dip angle is also the common method.

(2) Determining the drilling direction of drill bit. When the dip angle of target coal seam is determined, the relationship between deviation angle α and dip angle θ can be used to determine the drilling direction of the drill bit.

(3) Determining the position of drill bit in target coal seam. The distance between the drill bit and the interface of target coal seam usually can be calculated basing on the detecting depth of LWD tools. Moreover, according to the difference of gamma values in different strata of coal measures, as well as the different change laws of gamma value when crossing coal, dirt band, roof and floor, the bit position in coal seam and the lithology of stratum encountered can be identified in time. Six typical coal seam crossing methods, and trajectory tracking methods in the presence of faults are shown in Figs. 21 and 22.

3.4 Magnetic guidance drilling technology

In the process of drilling a CBM horizontal well, such as U/V-shaped or multilateral well, it is usually needed to intersect the horizontal well and vertical well in the target cave (Shi et al. 2011; Zhao et al. 2011; Qiao et al. 2021; Gao et al. 2022), which has a very high requirement for the control of wellbore trajectory and determination of drill bit location. However, due to the disadvantages of MWD/LWD such as measurement lag, low positioning accuracy and large accumulated errors, the intersecting operation frequently cannot be accomplished fluently, thus, the magnetic guidance drilling technology is usually required to be used in CBM horizontal drilling now.

Magnetic ranging technology is the key part of magnetic guidance drilling technology, it refers to the determination of relative distance and orientation from the well being drilled to a target well using the magnetic signature measurements (Grills 2002). According to different magnetic sources,

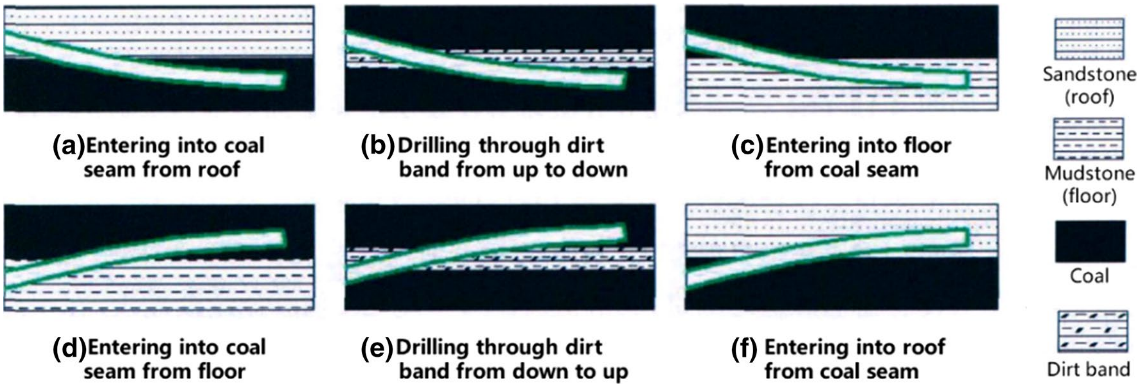


Fig. 21 Six typical coal seam crossing methods, modified from Zhao (2017)

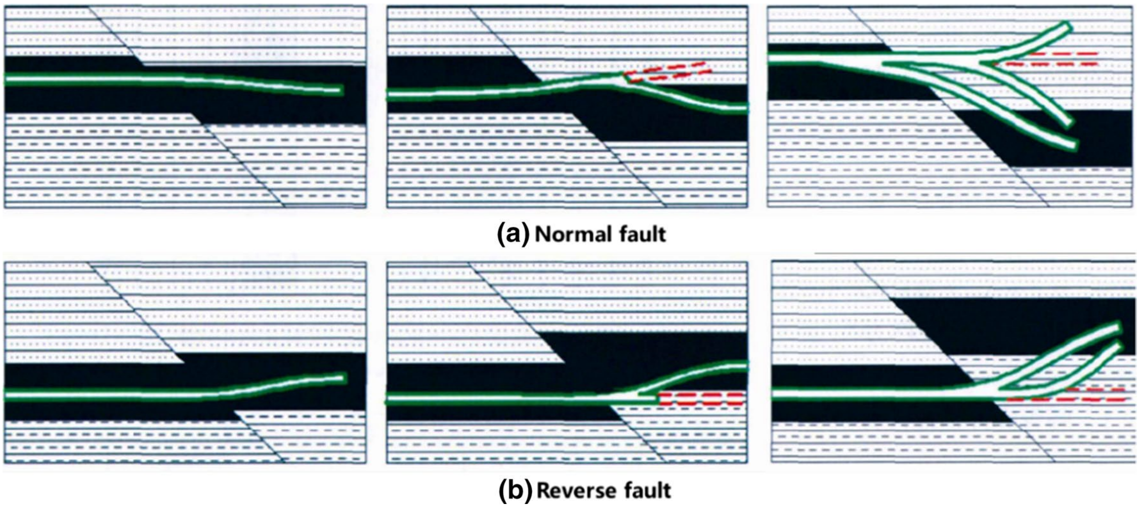


Fig. 22 Trajectory tracking methods in the presence of faults, modified from Zhao (2017)

magnetic ranging can be divided into active magnetic ranging and passive magnetic ranging. The active magnetic ranging can artificially change the magnetic field strength of the magnetic source by installing sensors or magnetic sources in the well being drilled or the target well, so as to measure the distance and orientation (Kuckes et al. 1996; Grills 2002), including Wellspot™ and WSAB™, Magnetic Guidance Tool™ (MGT), Single Wire Guidance™ (SWG), Rotating Magnet Ranging Service™ (RMRS) and DRMTS™. The passive magnetic ranging generally operates by measuring the current state of magnetization of the casing in the target well (Pratt and Hartman 1994; Grills 2002), such as Parallel Well Tracker™ (PWT) and MagTrac™. Different magnetic ranging technologies are compared and summarized in Table 5.

Nowadays, the magnetic ranging technology that is most commonly used in CBM horizontal well is the RMRS developed by Vector Magnetics company (Nekut et al. 2001; Rach 2004; Vandal et al. 2004; Oskarsen et al. 2009). In addition, the DRMTS that has the similar principle to RMRS was developed and used in China (Tian et al. 2012; Shen et al. 2017; Qiao et al. 2021).

RMRS is regarded as a typical example to explain the principle of CBM magnetic guidance drilling. As shown in Fig. 23, RMRS mainly consists of permanent magnetic sub and measuring probe in the downhole, signal acquisition device and data analysis system on the surface. The permanent magnetic sub is connected between the drill bit and PDM tool in the being drilled horizontal well, so as to generate a dynamically rotating magnetic field in the surrounding space as the drill bit rotates, thereby forming the magnetic source. The measuring probe is installed in the middle of the cave in the target vertical well, so as to detect and receive the generated magnetic signal. The received signals are processed by the downhole A/D conversion module, and transmitted to the surface through the cable. Thus, the relative distance and azimuth deviation between the drill bit and the target cave can be accurately calculated, the drilling

Table 5 Different magnetic ranging technologies

Type	Subtype	Magnetic source	Measuring range (m)	Application	Reference
Active magnetic ranging	Wellspot and WSAB	Casing that gathers current in the target well	-	Accident well Rescue well	Gao and Diao (2016); Zhang et al. (2019b)
	SWG	Current carrying conductor in the target well	100	Anti-collision of adjacent wells Intersection of two wells	Tarr et al. (1992); Mallary et al. (1998); Oskarsen et al. (2009)
	MGT	Energized solenoid in target well	30	SAGD well pairs	Kuckes et al. (1996); Vandal et al. (2004)
	RMRS	Permanent magnetic sub in the being drilled well	70	CBM horizontally intersected well SAGD well pairs	Nekut et al. (2001); Rach (2004); Vandal et al. (2004); Oskarsen et al. (2009)
	DRMTS	Magnetic sub in the being drilled well	110	CBM horizontally intersected well SAGD well pairs	Tian et al. (2012), Shen et al. (2017), Qiao et al. (2021)
Passive magnetic ranging	PWT	Magnetized casing in the target well	13	SAGD well pairs	Pratt et al. (1994), Kuckes et al. (1996)
	MagTrac	Magnetized casing in the target well	6–8	Anti-collision of adjacent well Rescue well	Grills (2002)

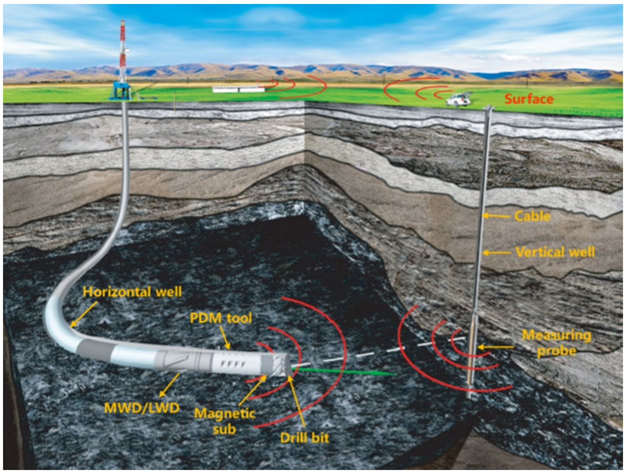


Fig. 23 Schematic of CBM magnetic guidance drilling using RMRS, modified from Gao and Diao (2016)

engineer then can adjust the wellbore trajectory to drill into the target cave in time. Measuring near the drill bit is the biggest advantage of RMRS, which makes the measurements more accurate and the positioning accuracy much higher. Moreover, as each data of RMRS is analyzed independently, there is no cumulative error with the change of well depth.

3.5 Underbalanced drilling technology

CBM reservoir is different from the ordinary oil and gas reservoirs, mainly in the unique seepage characteristic of natural cleat-fracture systems, stress sensitivity and vulnerability. The excessive density of drilling fluid is considered to be a main factor of CBM reservoir damage. Therefore, in order to achieve the purpose of protecting CBM reservoir and minimizing the adverse effects of drilling operation on CBM production, the underbalanced drilling (UBD) technology is an available and effective option (Xia et al. 2012; Shen et al. 2012, 2017; Gao et al. 2022).

Although UBD is the most ideal method for CBM drilling theoretically, the inevitable problem of wellbore instability is an important factor limiting its application in CBM drilling, especially for the CBM horizontal wells. Notably, gas-typed drilling fluids are the commonly used circulating medium in UBD, such as air, methane, nitrogen, mist, foam and aerated drilling fluid, and the aerated UBD technology has been promoted and applied for the horizontal drilling of CBM multilateral well to protect CBM reservoir (Duan et al. 2012; Lau et al. 2017; Gao et al. 2022). The aerated UBD pattern of CBM horizontal well is shown in Fig. 24, after the gas is injected into the cave through the tubing in vertical well, it is mixed with the drilling fluid to form a gas–liquid two-phase flow, which is then circulated in annulus and finally returned to surface from the horizontal well, thereby reducing the pressure of the annulus liquid column in the horizontal well, so as to decrease the drilling pollution to the CBM reservoir.

3.6 CBM drilling fluid

Reservoir protection is a crucial aspect in CBM drilling and completion, thus, except basic functions of drilling fluid,

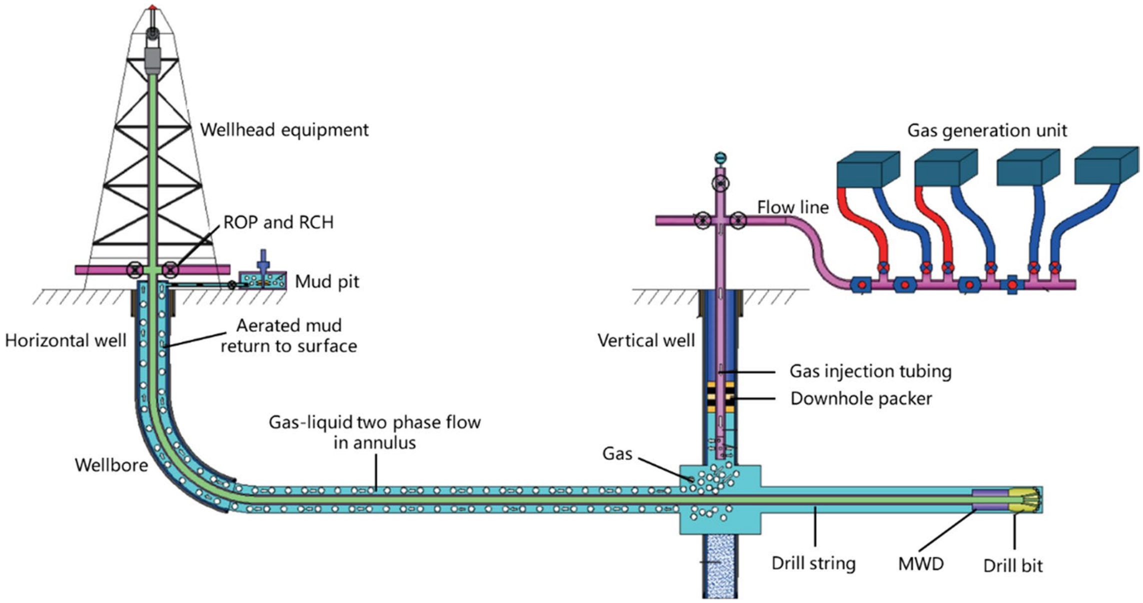


Fig. 24 Schematic of aerated UBD pattern of CBM horizontal well, modified from Gao et al. (2022)

CBM drilling fluid should have the characteristics of low solid content, low viscosity, low density, low water loss, good plugging and inhibition performance, so as to achieve the purpose of preventing coal seam collapse, leakage and pollution (Barr 2009; Ma et al. 2020b; Gao et al. 2022). Currently, different drilling fluids have been successfully applied to CBM drilling, and can be classified into two groups, i.e., water-based and gas-typed drilling fluids.

3.6.1 Water-based drilling fluid

Water-based drilling fluid is most commonly used in CBM drilling, its continuous phase is water. Clear water is frequently used in CBM drilling as the simplest mud, which contains no treating agent or additive. This mud can minimize the damage to coal seam, but its performances are general. Therefore, engineers often add bentonite, barite, chemical additives or treating agents to adjust the performance of mud to meet the requirements of the drilling operation. Various water-based muds have been developed and applied to CBM drilling, including clear water, solid-free/low solid drilling fluid (Sun et al. 2020), cenosphere drilling fluid (Xu et al. 2015), surfactant-MMH drilling fluid (Chen et al. 2019b), and degradable polymer drilling fluid (Lyu et al. 2019), as summarized in Table 6.

In addition, as the conventional water-based drilling fluids are usually not able to reconcile the contradiction between leakage under high-density condition and collapse under low-density, the fuzzy-ball drilling fluid is invented and successfully utilized in approximately 1000 CBM wells, and effectively solves the problems of wellbore instability and lost circulation (Zheng et al. 2012, 2016, 2018).

3.6.2 Gas-typed drilling fluid

Ideally, the most effective method of drilling a CBM well is gas drilling, which is operated in underbalanced condition with the minimal formation damage and contamination. In other words, gas-typed drilling fluids are the preferred muds for CBM drilling (Flores 2013). The continuous phase of the gas-typed drilling fluids can be the gas, such as air, methane, nitrogen and mist drilling fluid, and it also can be the liquid, such as foam and aerated drilling fluid, as summarized in Table 6. The air, methane or nitrogen are usually used in underbalanced drilling of vertical wells in low-pressure and stable CBM reservoir with low water production. Moreover, the mist or circulative micro foam drilling fluids are usually used to solve the water production problems that encountered in CBM drilling. The nanomaterials are now used to improve the stability of circulative micro foam drilling fluid (Cai et al. 2016; Li et al. 2022b). The aerated drilling fluid has been widely used in underbalanced drilling of CBM multilateral wells in China (Xia et al. 2012; Shen et al. 2012, 2017; Gao et al. 2022). In general, gas-typed drilling fluids have the advantage of lower density, better performance of carrying cuttings, significantly increasing drilling ROP, effectively preventing lost circulation and protecting coal seam.

Table 6 CBM drilling fluids and its features

Type	Sub-type	Features	Cost
Water-based muds	Clear water	Low damage to coal seam General performance	Low
	Solid-free/ low-solid mud	Solid-free/low solid, low density, low viscosity Preventing lost circulation Stabilizing wellbore Small damage to coal seam High drilling ROP	Medium
	Cenosphere mud	High bearing capacity Good rheological property Low filtration loss Good density adjustability, shear thinning, and thixotropy Available in deep CBM drilling	High
	Surfactant-MMH mud	Suppressing hydration expansion and dispersion of cuttings and clay Stabilizing wellbore Good rheological property	High
	Degradable polymer mud	Degradable polymer Stabilizing wellbore Preventing pollution and protecting coal seam	High
	Fuzzy-ball mud	Low density, low viscosity Solid-free Protecting coal seam Preventing lost circulation and wellbore collapse Available in underbalanced drilling of horizontal well	High
Gas-typed muds	Gas mud	Low density Good performance of carrying cuttings Increasing drilling ROP Preventing lost circulation Protecting coal seam Available in underbalanced drilling of CBM vertical well	Low
	Mist mud		Low
	Foam mud		Medium
	Aerated mud	Low density Preventing lost circulation and protecting coal seam Available in underbalanced drilling of CBM horizontal well	Medium

4 Key technologies of CBM completion

4.1 Open-hole completion series

4.1.1 Open-hole completion

The open-hole completion used for wells drilled in 1980s in the Black Warrior and San Juan Basins is the earliest completion method of single coal seam, and it is also the simplest completion method used in CBM well with the lowest costs and technical risks (Holditch 1993; Logan 1993; Palmer et al. 1993a, b; 1995, 2010). As shown in Fig. 25, when the bit drills to the top of coal seam, the casing is set and cemented, then drill bit is used to open the coal seam and form a completely exposed borehole, in which the screen or slotted liner can be run inside. Open-hole completion provides an unhindered contact to the coal seam surfaces from the wellbore, however, it is frequently plagued by the problem of wellbore collapse resulting in a constant block of the wellbore by coal fines or fragments. Although this problem can be remedied by packing the borehole with gravel, the coal fines still accumulate, which in turn, fill up the fractures and water pumps, finally, causing a reduced output of CBM. Therefore, the open-hole completion was rarely used in CBM vertical wells later, while its modified versions, such as open-hole cavity and under-ream completion, were developed and can be applied in some specific geological conditions.

4.1.2 Open-hole cavity completion

The open-hole cavity completion method was developed for CBM extraction of the San Juan basin fairway coals in 1985 (Holditch 1993; Logan et al. 1993; Palmer et al. 1993a, b, 1995; Shi et al. 2002). CBM wells completed by this method in the San Juan basin had gas production rates nearly ten times greater than it from vertical wells completed by fracture stimulation in the same area (Ramaswamy 2008; Palmer 2010). However, the open-hole cavity completion had been proved to work only under specific reservoir, geological, and geo-mechanical conditions (Holditch 1993).

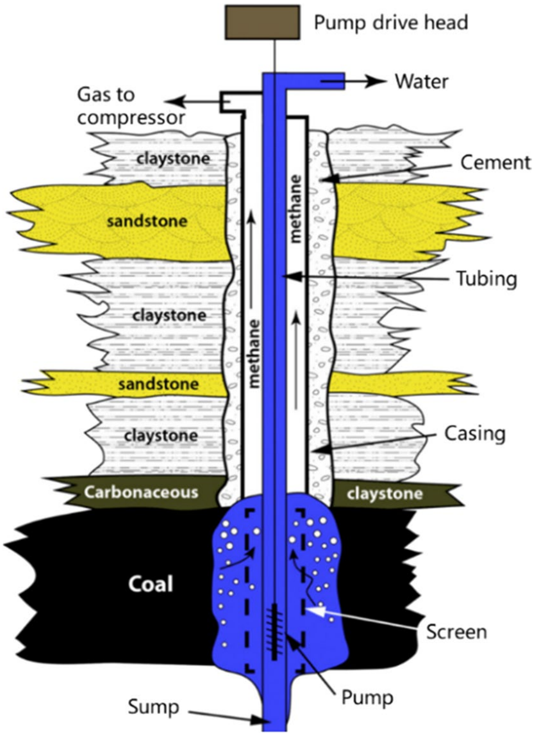
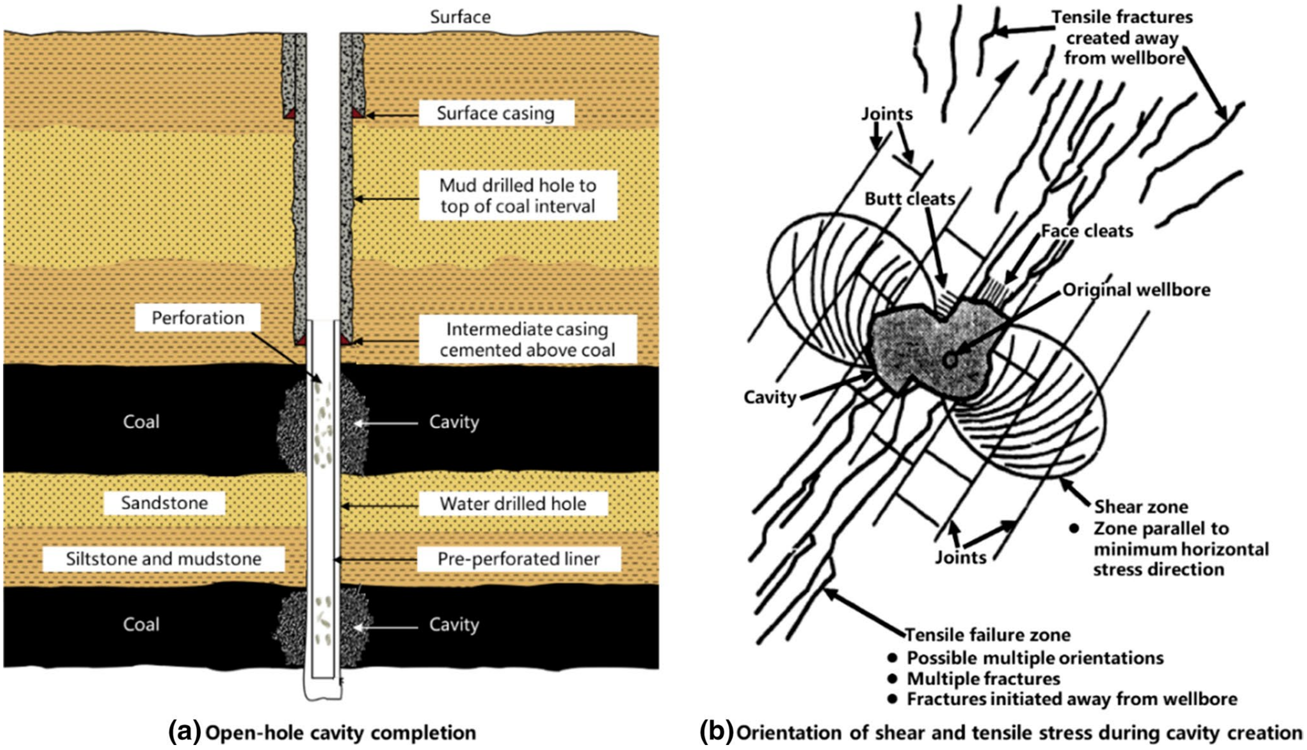


Fig. 25 Schematic of open-hole completion (Moore, 2012)

The open-hole cavity completion involves setting and cementing the casing only to the top of the coal seam. Then, the open-hole interval is drilled by using specially designed completion rig. To enhance the flow back and encourage coal sloughing in the wellbore, compressed air and air water mixture is injected into the wellbore, then, the surface valve is opened to rapidly reduce the wellbore pressure and blow out water, coal, and gas. This pressure fluctuation process results in the formation of a cavity around the wellbore. Repeating it and cleaning out the borehole continuously until the cavity is stable. After then, a pre-perforated, uncemented screen or liner can be run into the wellbore to maintain its long-term stability (Logan et al. 1993), as shown in Fig. 26a.

The wellbore condition is greatly improved through the cavitation process, which removes the drilling skin damage, eliminates the stress damage due to stress concentration around the wellbore, increases the connectivity of the coal seam to the wellbore, enlarges the physical wellbore radius, and probably enhances the permeability in the zone beyond the cavity surface significantly because the formation of a large unloading area with a number of induced fractures that can intersect the natural fractures around the wellbore (Mavor 1994; Palmer and Cameron 2003), as shown in Fig. 26b. However, this process has been successful only in fairway region of the San Juan basin in the US and a limited region of the Bowen basin, Australia (Palmer 2010). It had been identified that



(a) Open-hole cavity completion

(b) Orientation of shear and tensile stress during cavity creation

Fig. 26 Schematic of open-hole cavity completion, modified from Flores (2013) and Palmer et al. (1993a) the low compressive strength of coal (< 1000 psi), high permeability (> 20 mD), high- to medium-volatile bituminous coal rank, high gas content and reservoir overpressure are the main geologic conditions for a successful application of the open hole cavity completion (Ramaswamy 2008; Palmer 2010).

4.1.3 Under-ream completion

The under-ream completion method was developed in the 1990s for producing CBM from shallow coal seams in the Powder River basin (Palmer 2010). As shown in Fig. 27, the well is drilled to the top of the coal seam and the casing is set and cemented. Then, the well is drilled through the coal seam to form a normal borehole. Subsequently, under-ream operation can be achieving by running special under reamers, such as mechanical reaming tools and hydraulic jet tools, which can enlarge the borehole, remove any damage caused by drilling, overcome permeability damage due to stress concentration around the well, so as to enhance gas production (Ayers 2002; Palmer and Cameron 2003; Caballero 2013).

Actually, there are several important reasons for the success of under-ream completion in the Powder River basin (Ramaswamy 2008): permeability of the coal seam is very high (> 100 mD); coal rank and gas content are low; coal seams are thick (thickness > 30 ft) and continuous; coal seams are shallow (< 1800 ft), thereby the drilling cost is low, completion is very simple; and the stimulation treatment used is simple and inexpensive.

4.2 Cased-hole completion

Cased-hole completion is the most commonly used completion method for CBM wells, it is available no matter for a single coal seam or multiple coal seams within a coal zone or an interval, and these are usually the medium-to-low permeability (< 100 mD) coal seams. The use of cased-hole completion solves the wellbore collapse problems in open-hole completion, and it is allowed to implement the hydraulic fracturing stimulation treatment (Logan 1993).

As shown in Fig. 28, cased-hole completion uses a drill bit of the same size to drill through the coal seam to designed well depth, and the casing is set and cemented to the bottom of coal seam. Then, in order to provide an effective channel that communicates the coal seam with the wellbore, the casing is frequently required to be perforated, through which the hydraulic fracturing and gas production can be achieved. In general, the cased-hole completion with hydraulic fracturing is suitable for almost all types of coal seams, other than high permeability coal seams (> 100 mD), very low gas content coal seams (< 140 scf/t) (Ramaswamy 2008). Depending on the number of coal seams to be produced, the cased-hole completion could be single coalbed or multiple coalbeds completion. Deployment of cased-hole completion in multiple coalbeds technically makes production of CBM from thin coal beds feasible (Flores 2013).

4.3 Screen pipe completion

In order to solve problems related to blockage of wellbore caused by the pulverized coal production or coal seam collapse in open-hole completion, and the coal seam pollution

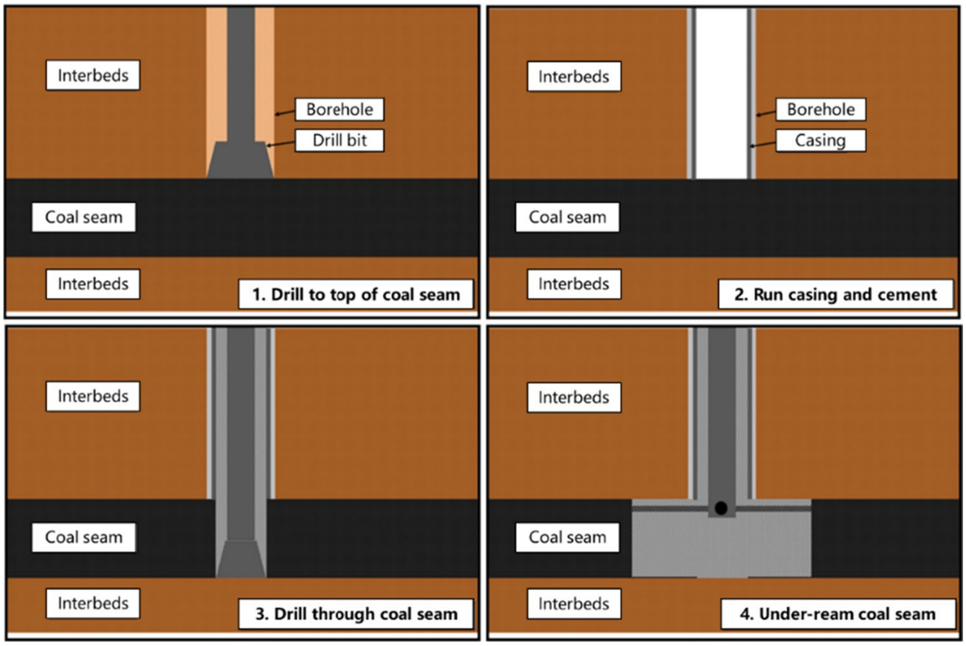


Fig. 27 Schematic of under-ream completion (Caballero 2013)

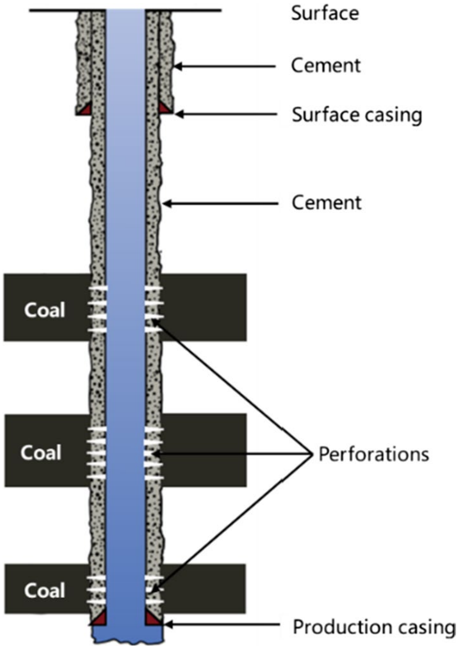


Fig. 28 Schematic of case-hole completion for multiple coalbeds, modified from Flores (2013)

during the cementing process in cased-hole completion, the screen pipe completion technology is regarded as a better completion method for CBM horizontal well. Nowadays, considering the safety of subsequent coal mining operation and the cost of completion, the use of metal slotted screen pipes is gradually reduced in CBM completion (Huang et al. 2012), while the application of non-metal slotted screen pipes is able to perform the low-cost completion of CBM wells and also beneficial to coal mining, including polyvinyl chloride (PVC), polyethylene (PE) and fiber reinforced plastic screen pipe (Shi et al. 2013; Zhao et al. 2014; Bi et al. 2016). A comparison between different screen pipes is summarized in Table 7. PE screen pipe completion is regarded as a typical example to introduce the principle of non-metal screen pipe completion, as shown in Fig. 29. PE screen pipe is one kind of continuous tube type, which has high compressive strength, safety factor, ring rigidity and good stress cracking resistance, and it can be run into the horizontal section through the inner hole of drilling pipe with injection (Shen et al. 2012). It is able to support the wellbore effectively, and provide a smooth flow channel for the coal powder, water and gas. The intermittent well washing operations also can be realized through the PE screen pipes.

In addition, some modified screen pipe completion methods are proposed to achieve a better completion effect, such as Bi et al. (2019) proposed a completion method that uses the flexible sieve tubes to solve the problem of wellbore collapse in CBM production for T-shaped well, Yang et al. (2019a) discussed the feasibility of the screen pipe completion technology used in the ultra-short radius horizontal well, Tan et al. (2020) proposed a re-entry screen completion technology for branched boreholes in CBM multilateral well, Xian et al. (2022) proposes a novel method of screen pipe completion and jet flow washing of horizontal well double tubular strings to enhance CBM recovery.

4.4 Horizontal well completion

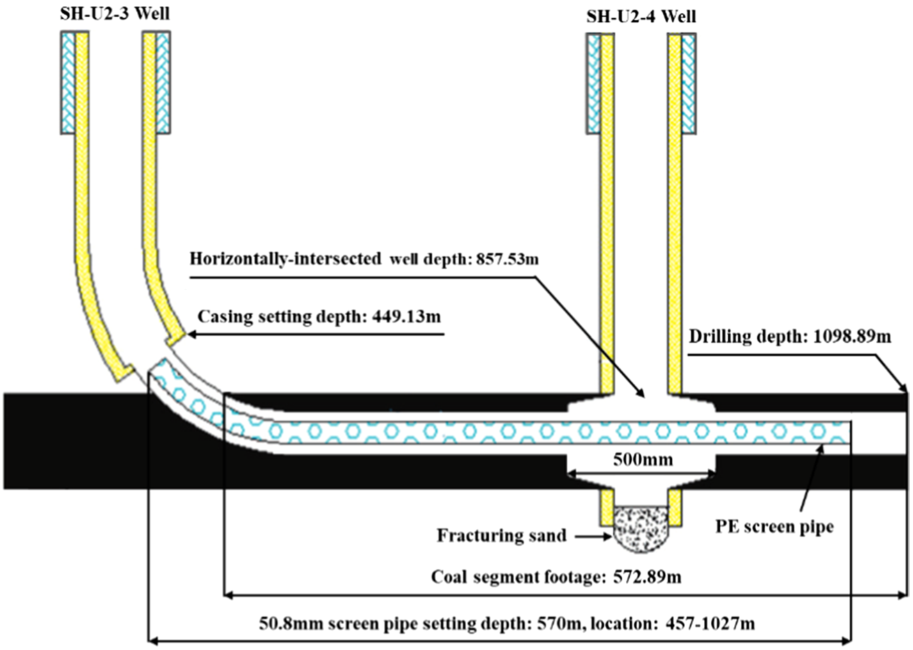
It is well known that the horizontal well technology plays an important role in CBM exploitation, it has significantly improved the CBM production. However, the cost of horizontal well drilling and completion is usually very high, so it is not suitable for all types of CBM reservoirs. Thereby, we have made an extra discussion and summary of CBM horizontal well completion methods.

The depth, thickness, areal extent, dip, permeability and mechanical strength of the coal seam are considered to be several main geologic factors that decide the selection of horizontal wells drilling and completion. According to the application of horizontal wells in the Appalachian, Arkoma, and some parts of San Juan basin, it is concluded that the horizontal well completion could be an available choice if the coal seam has the following properties: the thickness ranges from 3 to 20 ft, the areal extent is more than 1500 ft, the depth ranges from 500 to 4000 ft, the coal seam dip is less than 15 degrees, and the permeability is less than 20 mD (Ramaswamy 2008; Palmer 2010). Moreover, if the conditions for horizontal well drilling and completion are satisfied and the coal permeability is less than 5 mD, and the coal is free of intrusions and other complex geological

Table 7 Different screen pipes, after Huang et al. (2012), Shi et al. (2013) and Bi et al. (2016)

Type	Sub-type	Strength	Cost	Wellbore stability	Safety	Pipe reenter and well flushing	Operation difficulty
Mental screen pipe	Steel	High	High	Good	Bad	No	High
No-mental screen pipe	PVC	Low	Low	Bad	Good	Hard	Medium
	PE	Medium	Relatively low	Medium	Good	Easy	Relatively low
	Fiber reinforced plastic	Medium	Medium	Relatively good	Good	Easy	Low

Fig. 29 Schematic of PE screen pipe completion, modified from Zhao et al. (2014)



structures, such as folds and faults, then the drilling and completion of multilateral well is probably the best technology for improving CBM production, it has been successfully used in the Arkoma and Appalachian basins in US, and the Qinshui and Ordos Basins in China (Palmer 2010; Tao et al. 2019; Gao et al. 2022).

Actually, in addition to the screen pipe completion mentioned above, the open-hole completion and cased-hole completion are also two commonly used methods for CBM horizontal wells. Available completion methods for different horizontal well types and its characteristics are summarized in Table 8, while the specific implementation process of these three completion methods can refer to the literatures (Ramaswamy 2008; Caballero 2013; Shen et al. 2017; Gao et al. 2022). Especially, we have made a detailed introduction of completion methods for CBM multilateral horizontal well here. For a CBM multilateral horizontal well, maintaining both the main and lateral boreholes are open-hole is the most basic and simple completion method (Garrouch et al. 2004; Maricic et al. 2008; Keim et al. 2011). However, the wellbore stability usually cannot be guaranteed, and reentry into borehole, zonal isolation or selective control of production may be very difficult or even impossible. Thus, slotted liners or screens are highly recommended to be used in the boreholes to prevent it collapse (Ramaswamy 2008). Moreover, without considering subsequent coal mining, the main bore of the CBM multilateral well can be completed with casing and cement, thereby, realizing the long-term effectiveness and stability of the main bore gas production channel. While the lateral boreholes are open-hole, in which the screen can be run into to maintain its stability (Gentzis 2009; Ren et al. 2014; Tan et al. 2020). Segregated fracturing can be adopted in the main bore in this condition, so as to meet the requirements of reentry, maintainability and workability in the later stages, and increase CBM production (Tao et al. 2019).

Therefore, based on the above introduction of different completion technologies for CBM wells, meanwhile,

Table 8 Available completion methods for different horizontal well types, after Shen et al. (2017), Tao et al. (2019), Gao et al. (2022)

Horizontal well type	Available completion methods		
	Open-hole	Cased-hole	Screen pipe
L-shaped well	–	√	√
U/V-shaped well	–	√	√
Ultrashort-radius well	√	–	–
Multilateral well	√	√	–
Characteristics	Poor wellbore stability; Few stimulation and maintenance measures	Conducting perforation, segregated fracturing and wellbore reentry operation	Maintaining wellbore stability; Controlling pulverized coal production

combining the research works of selection methodology of drilling and completion techniques for CBM wells by Ramaswamy (2008) and Caballero (2013), and considering the following key reservoir parameters as main factors: net seam thickness, gas content, coal rank, coal seam depth, coal seam permeability, areal extent of coal seam, dip of the coal seam, number of coal seams, and vertical distribution of coal seam, a simple selection method of these mentioned completion technologies is summarized in Table 9.

5 Achievements, challenges and prospects

Throughout the development process of CBM around the world, it is clearly found that the development of DCT provides a very significant foundation. Since the first commercial vertical well for CBM exploitation was drilled in 1976, during the last fifty years, benefitting from the appearance of advanced technologies such as advanced directional drilling tools, measuring while drilling (MWD), geo-steering drilling (GSD), magnetic guidance drilling (MGD), managed pressure drilling (MPD), horizontal drilling, multilateral drilling, new drilling fluids, and advanced completion technologies, the CBM drilling technology has already advanced from the initially simple vertical drilling to currently various complicated horizontal drilling, such as the cluster well, L/U/V-shaped, ultrashort-radius and multilateral horizontal well, and the completion technology has correspondingly advanced from the simple open-hole completion to multiple advanced completion methods used for different CBM well types or coal seams with different geological conditions, such as open-hole cavity, under-ream, cased-hole with hydraulic fracturing, screen pipe and horizontal well completion, as summarized in Fig. 30. Lately, some other advanced technologies, including coiled tubing drilling, single trip drilling, factory horizontal well, infinitely fracturing horizontal well, novel non-mental screen pipe completion, are considered to be available options to help achieve the industry goal of an efficient, safe and economic drilling, completion and exploitation of CBM, while visualization, digitization, integration, informatization, automation and intelligence will be the future trend of CBM DCTs.

Table 9 The selection method of completion technologies for CBM well, after Ramaswamy (2008), Palmer (2010), Shen et al. (2017), Gao et al. (2022)

Completion methods	Key geologic parameters	Characteristics	Application
Open-hole completion	Strength and stability of coal	High coal strength Good wellbore stability	Rarely used in vertical wells; More used in multilateral horizontal wells
	Geologic structure of coal	Simple and complete coal structure	
Open-hole cavity completion	Compressive strength of coal	Low (< 1000 psi)	Vertical wells in San Juan basin in the US and in a limited region of the Bowen basin in Australia
	Permeability of coal	High (> 20 mD)	
	Coal rank	High- to medium-volatile bituminous coal rank	
	Gas content	High	
	Reservoir pressure	Reservoir overpressure	
Under-ream completion	Depth of coal seam	Shallow (< 1800 ft)	Vertical wells in the Powder River basin in the US
	Permeability of coal	Very high (> 100 mD)	
	Thickness of coal seam	Thick (> 30 ft)	
	Coal rank	Low	
	Gas content	Low	
Cased-hole with hydraulic fracturing completion	Permeability of coal	Not very high (1–100 mD)	Widely used in CBM vertical wells worldwide, such as the US, Australia, China
	Gas content	Not very low (> 140 scf/t)	
	Coal rank	High to low	
Scree pipe completion	PE and fiber reinforced plastic screen	Non-mental, slotted; Maintaining wellbore stability; Controlling pulverized coal production	L/U/V-shaped horizontal wells in China and Australia
Horizontal well completion	Thickness of coal seam	Thin (3–20 ft)	Horizontal wells in the Appalachian, Arkoma, and some parts of San Juan basin in the US, Bowen basin in Australia and Qinshui basin in China
	Areal extent	Large (> 1500 ft)	
	Depth of coal seam	Medium (500–4000 ft)	
	Dip of coal seam	Small (< 15 deg)	
	Permeability of coal	Low (< 20 mD); Much lower (< 5 mD) for multilateral well	

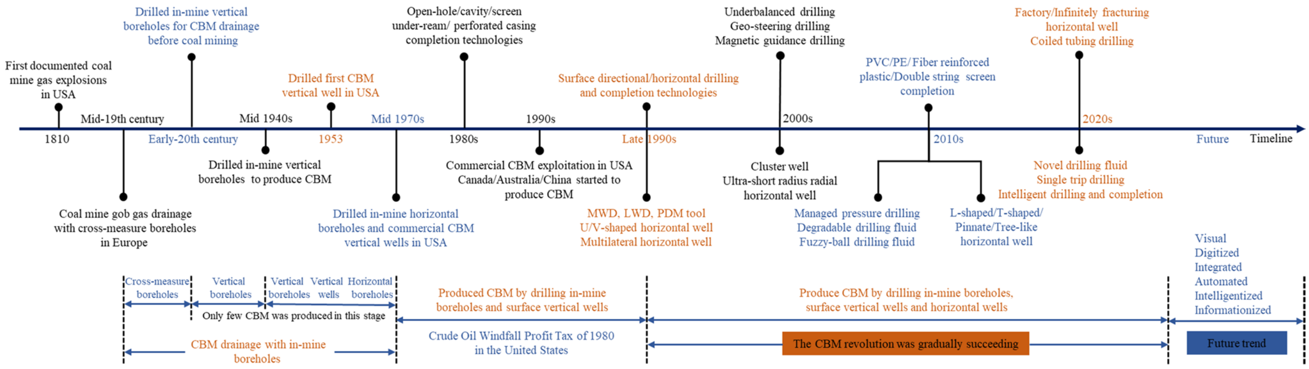


Fig. 30 Schematic of the developing process of CBM DCTs

A comprehensive identification of characteristics of different CBM reservoirs is a significant basis for the development and innovation of CBM DCTs, even more providing an important reference for the selection of optimal CBM DCTs. Detailed introduction and comparison of characteristics of different CBM reservoirs in the US, Australia and China can be obtain from the research works by Ramaswamy (2008), Li et al. (2018), Qin et al. (2018), Tao et al. (2019), Li et al. (2020b), Lu et al. (2021) and Gao et al. (2022). It is noteworthy that most of the commercial developing CBM reservoirs in China have the high coal rank (R_o of 0.58%–4.50%), low permeability (generally lower than 0.1 mD), high gas content (generally higher than 10 m^3/t), low reservoir pressure gradient (generally lower than 1 g/cm^3) and strong heterogeneity while compared with the US and Australia, but the CBM exploitation technologies used in China are similar to that in the US or Australia, especially the multilateral well technology used for CBM reservoirs with low permeability, thus, this may explain why China's CBM production is much lower than that of the US and Australia from the perspective of different characteristics of CBM reservoirs. In general, current worldwide lower CBM production indicates that the current technical system is not suitable for all kinds of CBM reservoirs or is not the optimal one, thus, overcoming current technical challenges and developing better technical system that matches with the characteristics of CBM reservoirs are the key to improve CBM production. Therefore, this paper summarizes current problems of CBM development from the perspective of CBM drilling and completion, and proposes corresponding suggestions and prospects as follows:

(1) Geological conditions of CBM reservoir. The particular reservoir characteristics of CBM are vital factors affecting its production, including coal rank, coal structure, coal depth and thickness, permeability, gas content, reservoir pressure and in situ stress regime (Ramaswamy 2008; Moore 2012; Li et al. 2020b). Nowadays, the success of CBM development in medium-low rank, medium–high permeability coals in the San Juan, Powder River, Uinta and Raton basins in the USA and in the Surat basins Australia has been well achieved (Pashin 1998; Ayers 2002; Lau et al. 2017; Li et al. 2018). However, there are many unsolved geological and engineering problems in the CBM development of medium–high rank, and low-permeability CBM reservoirs such as the Qinshui and Ordos basins in China (Qin et al. 2018; Cheng and Pan 2020; Lu et al. 2021; Gao et al. 2022). In other words, the current CBM developing technical system is not suitable for all kinds of CBM reservoirs. Therefore, on the one hand, continuing to focus on exploration and exploitation the medium to low rank coal reservoirs with practical development potential by applying and innovating current DCTs may yield better productivity, but it proposes much higher requirements for the exploration and evaluation technologies of CBM reservoirs. On the other hand, for CBM reservoirs with complex geological conditions and high developing difficulty, such as high rank, multiple, thin, deep, broken and high steep structure coal seams, in order to effectively reduce development costs and increase single-well production, reasonable selection and optimization of developing technology, innovations and breakthroughs in DCTs and reservoir stimulation measures are of significant importance.

(2) Optimization of well type. Different well type has different applicability to geological conditions of CBM reservoirs. Thus, the selection and optimization of well type became a crucial step in CBM drilling, especially for horizontal wells, in which comprehensively consider the petrographic characteristics of coal, development environment and later transformation of coal seam, and lithology combination characteristics of coal-bearing strata is essential (Tao et al. 2019; Gao et al. 2022). Higher investment cost and drilling accident rate, coexistence with higher production are the remarkable features of horizontal well, however, its geological applicability is very limited. Therefore, evaluating CBM reservoirs whether they are suitable for adapting horizontal well technology is of vital importance. After the well type is confirmed, the optimization of drilling method, well layout, design of wellbore structure and trajectory, and the branch number and distribution are all needed to conduct reasonably, so as to maximize the development benefit.

(3) Wellbore stability and reservoir protection. The contradiction between wellbore stability and reservoir protection has always been the main technical bottleneck restricting the large-scale application of CBM horizontal wells (Ma et al. 2015, 2018b; Zhang et al. 2017a; Gao et al. 2022). Although applying UBD technology is conductive to minimize reservoir damage, wellbore stability cannot be well guaranteed, which causing frequent downhole accidents. In order to prevent wellbore instability, balanced drilling and near-balanced drilling are adapted, while formation damage is inevitable, resulting in low productivity of CBM wells (Lau et al. 2017; Li et al. 2018; Lu et al. 2021). Therefore, quantitatively describing the mechanism of wellbore instability and reservoir damage of coal seams, and establishing a comprehensive evaluation method of wellbore stability while drilling a CBM well are urgently needed. Moreover, from the perspective of maintaining the original state of CBM reservoir in drilling process, developing new types of appropriative drilling fluid systems for coal seams, which can simultaneously achieve the performance of inhibiting wellbore collapse, leakage and low damage to CBM reservoir, such as fuzzy-ball drilling fluid, meanwhile, plugging and strengthening the coal seam wellbore, are probably two effective methods to guarantee safe and efficient drilling and protection of CBM reservoir. Furthermore, applying coiled tubing drilling technology into CBM horizontal wells for drilling a small wellbore or micro borehole, which is also beneficial to ensure wellbore stability.

(4) Economical, safe and efficient drilling technology. Realizing economic, safe and efficient drilling is the pursuing goal in CBM drilling. Undoubtedly, horizontal drilling technology will still be the preferred choice for economic exploitation of low-permeability CBM reservoirs, while the low-cost vertical drilling technology will be further popularized and applied to medium- and high- permeability CBM reservoir development to realize much lower development cost (Shen et al. 2017; Tao et al. 2019). Moreover, economic, safe and efficient drilling is inseparable from the application and development of advanced technologies, as following: ① CBM horizontal "well factory" pattern are the future trend and effective method to reduce exploitation costs and improve productivity; ② Adapting coiled tubing drilling technology, establishing risk monitoring, evaluation and control technology for CBM wells while drilling, and developing new drilling fluid system will change the status quo of high-risk drilling of CBM horizontal wells; ③ Using specialized vehicle-mounted drilling rigs will effectively improve drilling efficiency; combining UBD with horizontal drilling technology will better protect CBM reservoirs; advanced MWD, near-bit geo-steering technology, and MGD technology are conductive to realize the precise and efficient drilling operation of various complex CBM horizontal well type.

(5) Informationalized, automated and intelligent drilling. Adopting intelligent drilling tools (such as drilling rig, drill pipe, drill bit, coiled tubing, RSDS) and more advanced MWD, LWD, MGD, geo-steering technology in CBM drilling are overall trend of the future, in which the development of near-bit measurement and high-speed information transmission technology are particularly significant for achieving intelligent drilling (Li et al. 2020a; Wang and Guang 2020). Application of big data, machine learning, digital twin and artificial intelligence may be the important driving forces for achieving intelligent drilling. Although the use of advanced tools and technologies increases a certain cost, it also greatly saves manpower, operation time, and improves operation safety and efficiency, thus, it is ultimately beneficial to improve comprehensive developing benefits of CBM.

(6) Well completion technology. Selection of completion method is directly related to the cost of CBM development, single-well production, wellbore life and later drainage effects. Pulverized coal blocking, coal seam collapse, low productivity frequently occurs in open-hole completion, while the cased-hole completion with fracturing has problems such as unsatisfactory effect, high cost, and great impact on environment and later coal mining. Therefore, it is necessary to explore new completion technologies to maximize production benefits, as follows (Ramaswamy 2008; Caballero 2013; Palmer 2010; Shen et al. 2017; Gao et al. 2022): ① The open-hole cavity completion technology is still an available and effective completion choice for improving production for CBM vertical wells while the CBM reservoir properties meet its technical requirements; ② There are only limited completion methods used for CBM horizontal wells now, and their production stimulation effect is poor, so it is recommended to promoted and applied the novel screen pipe completion technologies for L/V/U-shaped well and ultra-short-radius well; ③ For low/ultra-low permeability CBM reservoirs, field tests of novel technologies such as open-hole ball sliding sleeve + open-hole packer, hydraulic sandblasting perforation, directional perforation, and infinitely staged fracturing should be to explore the best completion mode, such as for L/U-shaped well, multilateral well. In addition, on the basis of well completion technology, the application of some other advanced stimulation treatments is required to enhance CBM production, such as water jet slotting technique (Lin et al. 2015), hydraulic flushing technique (Zhang et al. 2019a), high-voltage electrical pulses technique (Yan et al. 2020), hydraulic grid slotting and fracturing technique (Li et al. 2017b; Zuo et al. 2020).

(7) Technology combination. In the context of current energy transition and carbon neutral, CBM, as an important and clean natural gas resource, it is of vital importance to achieve efficient exploitation of CBM to satisfy the need for energy (Zou et al. 2021). Therefore, in order to maximize the use of resources and protect the environment, combining CBM drilling technology with underground coal gasification technology and integrated coal production and gas extraction technology to realize the integrated green and efficient development of coal and CBM is one of the significant directions of CBM industry development. In recent years, three-gas co-exploration technique of CBM, tight sandstone gas, and shale gas with great development potential has also been proposed (Self et al. 2012; Yuan 2015; Zou et al. 2019; Lu et al. 2021). These all put forward a higher requirement for CBM DCTs to drill and complete a well that is able to achieve multiple functions.

6 Concluding remarks

This paper reviews the key technologies of CBM drilling and completion with the purpose of presenting its development status, recent achievements and challenges, future prospects, so as to achieve a more comprehensive understanding of CBM drilling and completion. Based on the findings of this work, it is found that the current technical system for CBM exploitation is not suitable for all kinds of CBM reservoirs, the CBM reservoirs with different characteristics require corresponding exploitation technologies, thus the selection of optimal well type, drilling and completion method is a crucial aspect. Moreover, safe, economic and efficient drilling and completion of CBM is inseparable from the support of advanced and innovated technologies, such as near-bit geo-steering drilling, novel drilling fluid, coiled tubing drilling, magnetic guidance drilling, novel screen pipe completion, horizontal well completion, and horizontal "well factory" mode. Furthermore, combining CBM DCTs with underground coal gasification technology, integrated coal production and gas extraction technology, and three-gas co-exploration technology to realize the integrated green and efficient development of coal and CBM is one of the most promoting directions of CBM industry development.

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Availability of data and materials All data generated or analysed during this study are included in this article.

Declarations

Competing interests The authors declare that there is no conflict of interest.

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