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Optimization of production well patterns for natural gas hydrate reservoir: Referring to the results from production tests and numerical simulations

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A B S T R A C T

Natural gas hydrate is a clean energy source with substantial resource potential. In contrast to conventional oil and gas, natural gas hydrate exists as a multi-phase system consisting of solids, liquids, and gases, which presents unique challenges and complicates the mechanisms of seepage and exploitation. Both domestic and international natural gas hydrate production tests typically employ a single-well production model. Although this approach has seen some success, it continues to be hindered by low production rates and short production cycles. Therefore, there is an urgent need to explore a new well network to significantly increase the production of a single well. This paper provides a comprehensive review of the latest advancements in natural gas hydrate research, including both laboratory studies and field tests. It further examines the gas production processes and development outcomes for single wells, dual wells, multi-branch wells, and multi-well systems under conditions of depressurization, thermal injection, and CO_2 replacement. On this basis, well types and well networks suitable for commercial exploitation of natural gas hydrate were explored, and the technical direction of natural gas hydrate development was proposed. The study shows that fully exploiting the flexibility of complex structural wells and designing a well network compatible with the reservoir is the key to improving production from a single well. Moreover, multi-well joint exploitation is identified as an effective strategy for achieving large-scale, efficient development of natural gas hydrate.

1. Introduction

Natural gas hydrate is a crystalline substance formed by the combination of natural gas and water under high pressure and low temperature, primarily in permafrost and offshore areas (Sloan ED and Koh CA, 2003). Its resource reserve is more than twice the size of conventional oil and gas resources globally (Beaudoin YC et al., 2014). Natural gas hydrates are regarded as one of the world's most promising clean energy sources (Makogon YF et al., 2007; Musakaey NG et al., 2018; Seol J and Lee H et al., 2013; Milkov AV, 2004).

In the 1960s, natural gas hydrates were first discovered in the permafrost during the development of the Messoyakha gas field in the former Soviet Union (Makogon YF et al., 2005, 2013). Since then, significant investments in research and exploration have been made globally, covering prospecting, basic geological studies, and production tests. In 1998, the first gas hydrate exploratory well was drilled in the Mackenzie Delta area of Canada. In 2002, the first gas hydrate production test was conducted in the Mallik permafrost area, using hot water circulation injection combined with the depressurization (Yamamoto K et al., 2008), with cumulative gas production of 468 m^3 over 5 days (Dallimore SR et al., 2005). In 2007−2008, Canada conducted a second test production using the depressurization method, achieving a cumulative gas production of 1.3×10^4 m^3 in 6 days (Li XS et al., 2016; Kurihara M et al., 2010). In 2012,

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the CO_2-CH_4 replacement method was used in a permafrost gas hydrate test production in the Ignik Sikumi #1 well on the North Slope of Alaska, USA, with a cumulative gas production of 2.8317 × 10^4 m^3 over 30 days (Anderson BJ et al., 2011; Collett TS et al., 2012).

Marine hydrate development began later but progressed rapidly. In 2013, Japan conducted the world's first production test of marine gas hydrates in the Eastern Nankai Trough, with a cumulative gas production of 1.2 × 10^5 m^3 over 6 days (Suzuki K et al., 2015; Yamamoto K et al., 2019). In 2017, the second production test was conducted with two wells: the first well was produced for 12 days, with a cumulative gas production of 4.1×10^4 m^3. while the second well was produced for 24 days, with a cumulative gas production of 2.23 × 10^5 m^3 (Yamamoto K et al., 2014; Fujii T et al., 2015; Tamaki M et al., 2017). In 2017, China conducted the first direct well depressurization test in the Shenhu area of the South China Sea, resulting in continuous stable gas production for 60 days and cumulative gas production of 3.1×10^5 m^3 (Li JF et al., 2018). In 2020, the second test also utilized the first horizontal well for production, resulting in continuous stable gas production for 30 days and cumulative gas production of 8.614×$10^5$$m^3$ (Ye JL et al., 2020). China has set world records for gas hydrate production tests, including the longest continuous test time, the highest daily production rate of a single well, and the largest cumulative gas production (Qin XW et al., 2022).

When analyzing the global hydrate test production (Table 1), from permafrost hydrate to marine hydrate test production, the reservoir lithology ranges from coarse sand to fine sand to muddy siltstone. Reservoirs are becoming increasingly tight. Boswell R and Collett TS (2011) proposed the Gas Hydrate Resource Pyramid model, which suggests that over 90% of the world's gas hydrates are located in clayey siltstone or silty sediments with low permeability on the seafloor (You K et al., 2019). These resources, located at the bottom of the pyramid and are the largest but most challenging to develop. China has successfully tested muddy siltstone gas hydrates in the Shenhu Sea in the South China Sea, confirming the feasibility of producing this resource on the seafloor. These tests represent a milestone in the history of the global development of natural gas hydrate and will further deepen the international gas hydrate research community's understanding of the potential of hydrate resources (Li JF et al., 2018; Ye JL et al., 2020). Hydrate exploitation has garnered substantial global attention and has become a subject of extensive research interest.

Although gas hydrate test production in domestic and foreign countries has achieved some success, it still faces the status of low gas production and short exploitation cycle, mainly using a single-well type exploitation scheme (Moridis GJ et al., 2007a, 2007b, 2008b; Chong ZR et al., 2017), and this method is still unable to meet the requirements of large-scale commercialized production of natural gas hydrates. Reasonably well placement is the technical key to increasing the production capacity of a single well and realizing the commercial exploitation of gas hydrates. Therefore, researchers worldwide are increasingly focusing on studying dual-well, multi-branch, and multi-well production schemes. In dual-well production, both dual vertical wells and dual horizontal wells, when two wells are simultaneously produced with depressurization, pressure interference is generated between the two wells, which will further accelerate the exploitation of hydrates (Yu T et al.,2019; Chen CY et al., 2020). When the two wells are exploited by depressurization and joint heat injection since depressurization is a process of heat absorption and heat injection can supplement the heat promptly, the risk of secondary hydrate formation can be reduced, which can significantly improve the recovery rate (Yang H et al., 2012; Loh M et al., 2015). Recently, many

Table 1. Summary of global gas hydrate production tests in permafrost and marine areas.

Year	Field location	Reservoir lithology	Well-type	Production method	Production Duration (days)	Cumulative Gas volume (ST m^3)	Average rate (ST m^3/day)	References
2002	Mallik site, Mackenzie Delta, Canada	Coarse sand	Vertical	Thermal stimulation	5	468	94	Yamamoto K et al., 2008 Dallimore SR et al., 2005
2007			Vertical	Depressurization	0.5	830	1660	Li XS et al., 2016
2008			Vertical	Depressurization	6	13000	2167	Kurihara M, et al., 2010
2012	Prudhoe Bay Unit, Alaska North Slope, USA	Coarse sand	Vertical	CO_2-CH_4 exchange	30	24410	814	Anderson BJ et al., 2011 Collett TS et al., 2012
2013	Eastern Nankai Trough, Japan	Sandy Turbidite sediments	Vertical	Depressurization	6	119500	19917	Suzuki K et al., 2015 Yamamoto K et al., 2019
2017			Vertical	Depressurization	12	41000	3417	Yamamoto K et al., 2014 Fujii T et al., 2015
2017			Vertical	Depressurization	24	222500	9271	Tamaki M et al., 2017
2017	Shenhu area, South China Sea, China	Clayey Silt	Vertical	Depressurization	60	309000	5150	Li JF et al., 2018
2020			Horizontal	Depressurization	30	861400	28,713	Ye JL et al., 2020

scholars have studied the production enhancement effect of complex structure wells represented by multi-branch wells. Compared with single well type, multi-branch wells can significantly increase the disintegrated area, branch length and number of branches, further increasing gas production (Zhang PP et al., 2022, 2021; Ye H et al., 2021, 2022). At the same time, a multi-fractured multilateral well network is used, which, on the one hand, can synergize the interference between multiple branch wells. On the other hand, multi-fractures increase the seepage capacity and two can significantly increase the production of a single well (Mao PX et al., 2021, 2023). Currently, the multi-well scheme is limited to laboratory and conceptual well network numerical simulation, and it needs to be explored in depth according to the geological conditions of the actual hydrate reservoirs.

Based on a review of natural gas hydrate experiments, field tests, and numerical simulation studies, this paper comprehensively summarizes the latest progress in well network design, discusses the applicable conditions, advantages, and disadvantages of different well types and networks, and provides insights into well types and network design for hydrate exploitation.

This paper is structured as follows: Section 2 introduces the classification of gas hydrate reservoirs; Section 3 summarizes the potential exploitation methods of natural gas hydrate; Section 4 systematically describes the single-well, dual-well, multi-branch well and multi-well exploitation schemes of natural gas hydrate; the applicable conditions, advantages and disadvantages of different well distribution methods of natural gas hydrate are discussed in section 5; lastly, Section 6 summarizes the relationship between well type, well pattern and production mode, and puts forward the research direction for hydrate well pattern development.

2. Natural gas hydrate reservoir characteristics

According to the hydrate content and trap structure of hydrate-hosting sediments, hydrate reservoirs can be classified into four types (Moridis GJ et al., 2006). This paper further characterizes the four types of hydrate, as shown in Fig. 1.

For Class 1 hydrate reservoir, free gas layers are beneath hydrate-bearing layers, which are sandwiched by impermeable overburden and underburden layers. The Class 1 hydrate reservoirs can be further classified into Class 1W and 1G hydrate reservoirs according to the phase state of hydrate layers. Class 1W hydrate reservoirs fill liquid water in the pores, and Class 1G hydrate reservoirs are filled with free gas in the pores. In Class 1 hydrate reservoirs, the hydrate at the bottom of hydrate-bearing layers is generally at the critical point of phase equilibrium since the bottom of these layers coincides with the bottom of the hydrate stability zone. only small changes in pressure and temperature around this bottom can induce effective hydrate dissociation into methane gas and water (Moridis GJ and Collett TS, 2003). Therefore, Class 1 hydrate reservoirs are expected to have the greatest development potential (Moridis GJ and Collett TS, 2003; Alp D et al., 2007).

Class 2 hydrate reservoirs include hydrate-bearing layers, water layers and impermeable overburden and underburden layers. The whole hydrate occurrence interval lies within the hydrate stability zone.

Class 3 hydrate reservoirs only include hydrate layers and impermeable overburden and underburden layers. Generally, the hydrate-bearing layer has good permeability and high hydrate saturation. The whole hydrate occurrence interval lies within the hydrate stability zone.

Class 4 hydrate reservoirs, mainly referring to marine hydrates, have almost the same structure as Class 3 reservoirs. Yet, the permeability of hydrate-bearing layers is much lower, the hydrate spatial distribution is more scattered, hydrate saturation is generally less than 10%, and impermeable overburden and underburden layers are difficult to detect. Although Class 4 accounts for a high proportion of hydrate reserves, it is quite challenging to exploit such types of hydrate reservoirs by conventional methods (Moridis GJ et al., 2009).

It is believed that Class 1 and Class 2 hydrate reservoirs can be exploited effectively by the depressurization method (Moridis GJ and Collett TS, 2003; Bybee K 2007). However, only the depressurization method cannot handle the scenarios of Class 3 and Class 4 hydrate reservoirs (Yang SH et al., 2014) since the recovery rate is low. Therefore, it is necessary to adopt the combined exploitation methods of depressurization and heat injection to obtain higher methane production (Moridis GJ et al., 2007; Moridis GJ and Reagan

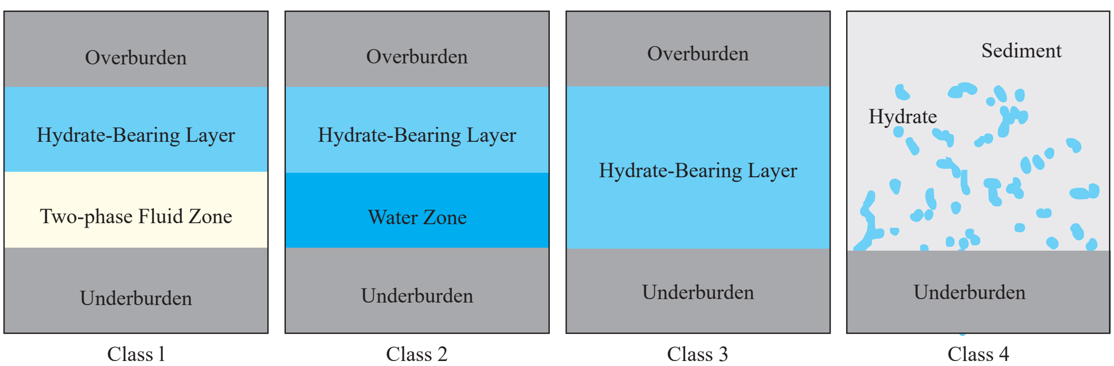

Fig. 1. Schematic diagram of hydrate classification.

MT, 2007).

3. Recovery mechanisms of Natural Gas Hydrate

Unlike the exploitation of conventional energy resources such as oil and gas, the exploitation of natural gas hydrate is particular in complicated phase behaviors such as hydrate dissociation. The initial state of conventional fossil energy is either gas or liquid, whereas hydrate is initially solid. During hydrate exploitation, the phase equilibrium is broken due to changes in temperature and pressure, and the hydrate changes from a solid state to a gaseous natural gas-liquid water (Koh DY et al., 2016). The main methods of natural gas hydrate exploitation proposed by scholars both domestically and abroad include depressurization, heat injection, chemical inhibitor injection, CO_2 replacement, and solid-state fluidization (Koh DY et al., 2016; Xu CG et al., 2015; Li SX et al., 2016). The recovery principles are shown in Fig. 2. Table 2 compares the advantages and disadvantages of different hydrate recovery methods.

Numerous studies and tests have demonstrated the

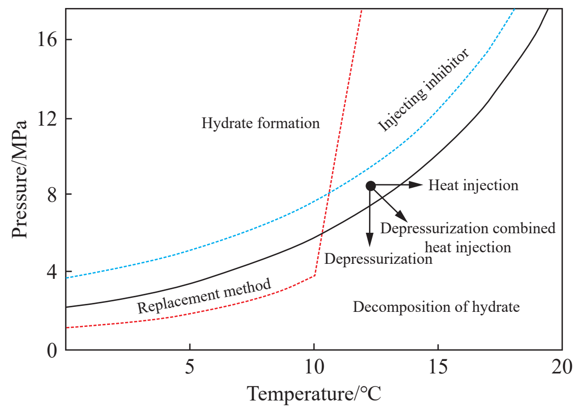

Fig. 2. Principles of different recovery methods of hydrate.

Table 2. Comparison of advantages and disadvantages of different hydrate recovery methods.

Recovery methods	Recovery mechanisms	Advantages	Disadvantages	Production test Region	References
Depressurization	Under constant reservoir temperature, the hydrate's reservoir pressure is reduced below the equilibrium pressure, causing it to decompose.	The most cost-effective and most straightforward method of production High efficiency of recovery and simple construction.	It is not suitable for low permeability and shallow buried reservoirs. It easily forms ice and secondary hydrates, as well as sand.	Eastern Nankai Trough, Japan; Shenhu area, South China Sea, China	Moridis GJ and Collett TS, 2003 Makogon YF et al., 2005; 2013 Yu T et al., 2019 Shang SL et al., 2021
Thermal Stimulation	By raising the wellhead or formation temperature, the formation temperature is higher than the phase equilibrium temperature and the hydrate decomposes.	The injected heat can efficiently manage the rate of hydrate decomposition.	Significant heat dissipation within the upper and lower boundary layers results in substantial heat loss.	Mallik site, Mackenzie Delta, Canada	Liu B et al., 2012 Zhang XH et al., 2019 Feng YC et al., 2021 Li QP et al., 2022
Inhibitor injection	Methanol, ethanol, salt water, and other inhibiting substances are injected into the hydrate reserve to alter the phase equilibrium curve and encourage the decomposition of the hydrate.	It can increase the rate of exploitation in a short time. Simple operation and energy efficiency.	It is challenging to inject into reservoirs with low permeability efficiently. Additionally, this process can cause environmental pollution	Messoyakha, Russia	Li XS et al., 2016 Collett TS et al., 2012 He T et al., 2017 Qin HB, 2016 Zhang YT et al., 2023
CO_2 Replacement	The process of injecting CO_2 or other gases which have a greater tendency to form hydrates than methane, to displace methane from the hydrate cage structure	It can effectively sequester carbon dioxide in the seabed while maintaining reservoir stability.	The displacement rate of CO_2 is slow. Limited by the availability of the gas source.	Prudhoe bay Unit, Alaska North slope, USA	Sun ZX et al., 2020 Hauge LP et al., 2014
Solid State Fluidization	The natural gas hydrate ore body is mechanically crushed and processed into hydrate mud, which is then lifted onto the drilling platform. There, the hydrate gradually dissolves due to changes in temperature and pressure.	The recovery process is safe and controllable. Suitable for shallow burial and concentrated distribution of large blocks.	The technical difficulties are high, energy utilization is low, and seabed digging can cause ground disturbance.	Liwan, Northern South China Sea, China	Zhou SW et al., 2014; 2018 Zhao JZ et al., 2017 Zhao J et al., 2020
Joint exploitation	The primary objective is to reduce pressure, which can be achieved through heat injection, inhibitor injection, or CO_2 replacement. Among these methods, the depressurization + heat injection method solves the problem of insufficient heat in the depressurization process by heat injection.	Maximize the depressurization while also utilizing other methods to increase production.	The technical equipment and test conditions are not yet fully developed.	Mallik site, Mackenzie Delta, Canada	Loh M et al., 2015 Li B et al., 2016 Liu YG et al., 2019

feasibility of simple depressurization. However, its efficiency is limited, and it can cause significant sand hazards in sandstone areas. Similarly, simple heat and inhibitor injection efficiency is also low. To enhance hydrate exploitation's efficiency, safety, and applicability, selecting appropriate methods for different reservoir conditions is necessary, especially considering the joint exploitation of different methods (Zhang XH et al., 2019). Depressurization is typically the primary method used for exploitation, and more than two methods, such as combined heat injection or combined inhibitor injection, are used (Loh M et al., 2015; Sasaki K et al., 2009; Moridis GJ et al., 2009, 2011; Liu YG et al., 2019; Wang Y et al. 2014; Sun ZX et al., 2020). Furthermore, unconventional oil and gas resources, such as shale gas and tight oil, have been introduced into the field of hydrate development to enhance production. With the discovery of an increasing number of low-permeability reservoirs, hydraulic fracturing modification combined with depressurization methods are considered potential recovery methods (Feng YC et al., 2019; Sun JX al., 2019). The authors aim to develop an efficient and safe hydrate exploitation technology by combining the advantages of multiple methods.

4. Well pattern for natural gas hydrate exploitation

By the end of 2019, traditional vertical wells had been widely used for production tests worldwide. For instance, vertical wells were used for the first production test in Alaska in the United States, the Nankai Trough in Japan, and the Shenhu area in China. Further, in 2020, horizontal wells were used for the second production test in the Shenhu area in China, which is the only successful case using horizontal wells to realize natural gas hydrate production test worldwide (Ye JL et al., 2020).

With the deepening of research, the design of well spacing patterns for hydrate exploitation has received much attention. In recent years, the research on well pattern design has transitioned from single vertical wells and single horizontal wells to multi-vertical well, multi-horizontal well, and multi-branch horizontal wells. When using multiple wells, the main mechanisms of improving hydrate production efficiency include several aspects: Firstly, expanding the decomposition interface and increasing the outflow area; secondly, improving the decomposition rate of natural gas hydrate; thirdly, improving the reservoir seepage conditions (Wu NY et al., 2020). The forthcoming sections will assess sequentially single-well exploitation, dual-well exploitation, and multi-well exploitation.

4.1. Single Well Exploitation Scheme

4.1.1. Vertical well

Vertical well exploitation is currently the most widely used hydrate exploitation scheme. Moridis GJ et al. (2007a) analyzed the production potential and reservoir response of two hydrate reservoirs based on the sedimentary characteristics of Class 1 hydrate reservoir (free gas present under the hydrate layer). (Moridis GJ and Reagan MT 2007a; 2007b) studied the development strategies of Class 2 and 3 hydrates. Comparison of Two Types of Class 1 Hydrates: According to studies by Moridis GJ and Reagan MT (2007a), the decomposition gas volume of 1W hydrate can reach up to 65%, while that of 1G hydrate is 75%. As this study suggested, Class 1 gas hydrates can be the preferred target for future production. In Class 2 hydrate reservoirs, the low compressibility of water leads to an obvious decompression effect, and gas production accounts for about 74% of the decomposed gas volume (Moridis GJ and Kowalsky M, 2006). For Class 3 hydrates, natural gas production increases as the hydrate temperature increases, the intrinsic permeability increases, and the hydrate saturation decreases (Moridis GJ and Reagan MT, 2007a). Therefore, Vertical wells are suitable for Class 1 hydrate reservoirs with free gas layers. By drilling these wells vertically below the hydrate layer, gas can be produced directly from gas reservoirs, reducing the hydrate reservoir's pressure and making hydrate production more economical.

4.1.2. Directional wells

Directional wells primarily refer to wells with a large inclination angle. Compared to vertical wells, they align the wellbore with the pre-designed trajectory. This operation improves the contact area between the wellbore and reservoir, resulting in higher production from a single well. Directional wells are particularly suitable for sites with complex geological and surface conditions. For example, the reservoir is relatively developed, but the vertical continuity of the hydrate reservoirs is not good, or hydrate reservoirs are in the ocean and another special environment. Myshakin EM et al. (2016) simulated the depressurization exploitation of the hydrate reservoir in the Alaskan North Slope using both vertical and inclined wells (Fig. 3). This reservoir has a dip angle of approximately 30°. It includes two target layers: D and C sand layers, with thicknesses of around 20 m and 50 m, respectively. It is shown that the contact area between the directional well and the hydrate reservoir is much larger than that of the vertical well, and the daily gas production rate is 75% higher than that of the vertical well. These findings suggest that the gas production rate of the Directional well scheme is significantly higher than that of the vertical well.

4.1.3. Horizontal well

horizontal wells represent a specific case of directional wells, with a maximum inclination of nearly 90° for a certain length of horizontal well section in the target zone. The employment of horizontal wells provides an opportunity to increase the production of a single well during development significantly. Moridis GJ et al. (2008b) first compared the efficiency of horizontal and vertical wells in diverse reservoir types and concluded that in Class I reservoirs, both horizontal and vertical wells would result in the advancement of gas hydrates decomposition along the interface between hydrate

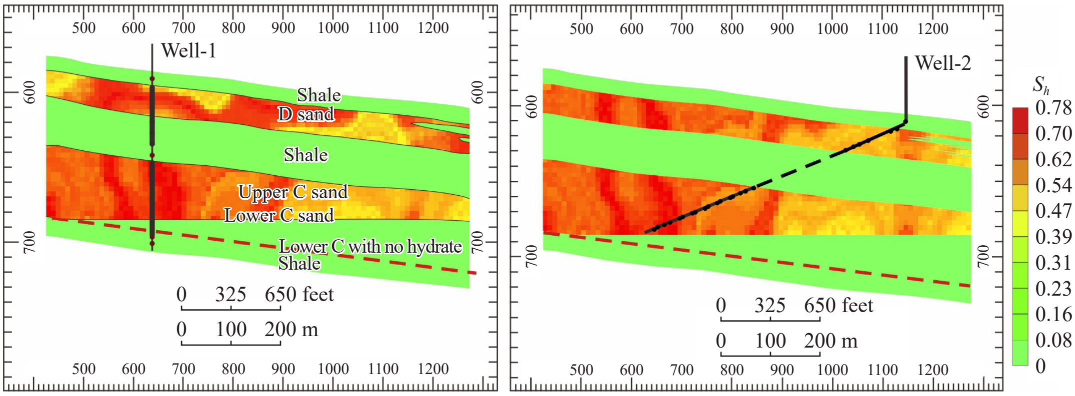

Fig. 3. Hydrate saturation distribution in the plane of the vertical well (“Well-1”) and the inclined well (“Well-2”) (modified from Myshakin EM et al., 2016).

and free gas layer. As their results suggested, Horizontal wells have a limited positive effect on gas hydrate decomposition in Class 1 reservoirs while they can significantly increase production in Class 2 and Class 3 reservoirs. The effective stimulation period was closely related to the location of horizontal wells.

Scientists at both domestic and international levels have conducted many simulation studies based on field survey data, focusing mainly on the current hot spots of hydrate research. Moridis GJ et al. (2011) investigated the gas production characteristics of Class 3 hydrate using horizontal and vertical wells in Unit D, Kupaluk River area, Prudhoe Bay, northern Alaska. They found that methane production from the horizontal well is two orders of magnitude higher than from the vertical well. A temperature rise of 1°C resulted in an eightfold increase in methane production, while water production remained unchanged. Feng YC et al. (2019) compared the production capacity of vertical and horizontal wells by simulating Class 2 hydrate exploitation at the AT1 test production site in the Nankai Trough, Japan. After one year of production simulation, horizontal wells could increase methane production in sandy reservoirs by magnitude. Li SX et al. (2020) developed an experimental model depicting the multi-layer Class 3 hydrate in Shenhu, South China Sea. They found that the average daily gas production of the horizontal well is twice that of the vertical well after 2000 days of simulated production. Using horizontal wells, Cheng YH et al. (2022) studied the effect of hydraulic fracturing on methane production of Class 3 hydrate in Shenhu, South China Sea. In a simulation of 1000 days, the cumulative methane production with horizontal and vertical fractures increased by 306% and 550%, respectively, compared to that without fractures. This suggests that depressurization combined with hydraulic fracturing via horizontal wells has a good potential for production in hydrate exploitation.

Horizontal wells can greatly improve the productivity of natural gas hydrate because of several advantages, increasing the contact area between the wellbore and natural gas hydrate reservoir, expanding the decomposition front of natural gas hydrate, and doubling the volume of natural gas hydrate involved in decomposition at the same time. Wu NY et al. (2020) The second hydrate test in China’s Shenhu Sea has also fully confirmed the production-enhancing effect of horizontal drilling.

4.2. Dual Well Exploitation Scheme

Double-well exploitation scheme has greater potential for gas hydrate production than a single-well exploitation scheme. Although the employment of double vertical or horizontal wells does not strictly adhere to a “well pattern”, it provides important guidance for the design of multi-well patterns. The double wells can be two vertical wells, one vertical and one horizontal well, or two horizontal wells, typically featuring separate injection and production.

4.2.1. Two vertical wells

The two vertical wells can be used for depressurization and combined heat injection production, i.e., one well is used for heat injection, and the other is used for depressurization. The following section compares the gas production characteristics under both production conditions.

Regarding the depressurization of double vertical wells, Yu T et al. (2019) performed a numerical simulation on the long-term production dynamics of natural gas hydrate in the Nankai Trough in Japan. Their study mainly focused on comparing the productivity of a single vertical well and double vertical wells under the depressurization method (Fig. 4). After 15 years of depressurization, it has been found that the total gas production of double vertical wells is twice that of a single vertical well. When double wells are employed, the hydrate dissociation ratio can reach 87.8%, significantly higher than the 45.5% in the case of a single vertical well. Chen CY et al. (2020) carried out a numerical simulation of the depressurization of Class 1 natural gas hydrate reservoir with low permeability at the W17 site in the northern South China Sea in 2017 (Fig. 5). Compare the employment of single well, the average controlling area of each borehole decreases and the average production rates of gas/water of single borehole decrease in the case of double vertical wells. However, dual vertical boreholes' overall gas production and hydrate recovery are greater.

Regarding the method of dual vertical well

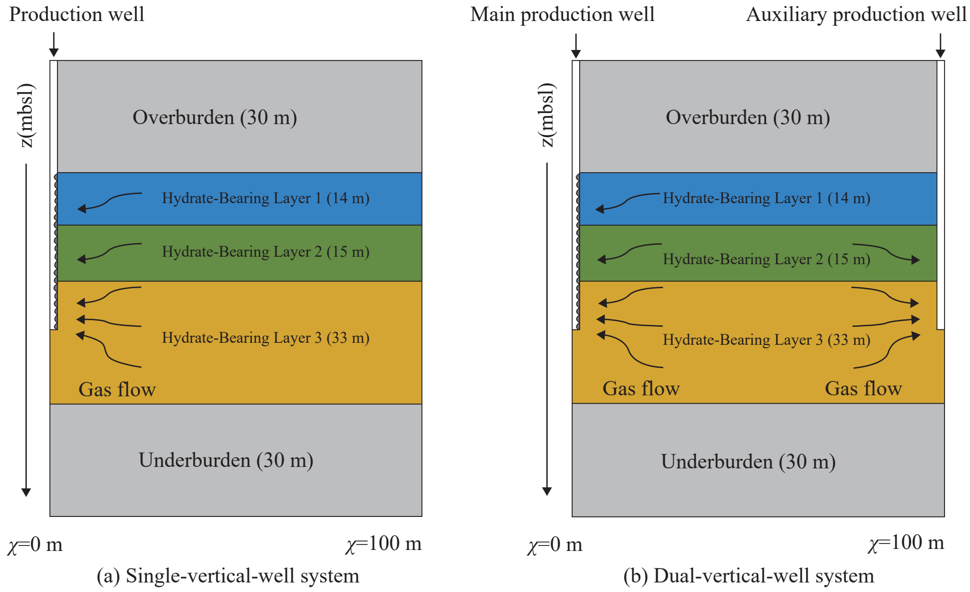

Fig. 4. Well configurations for the oceanic gas hydrate production by depressurization (modified from Yu T et al., 2019).

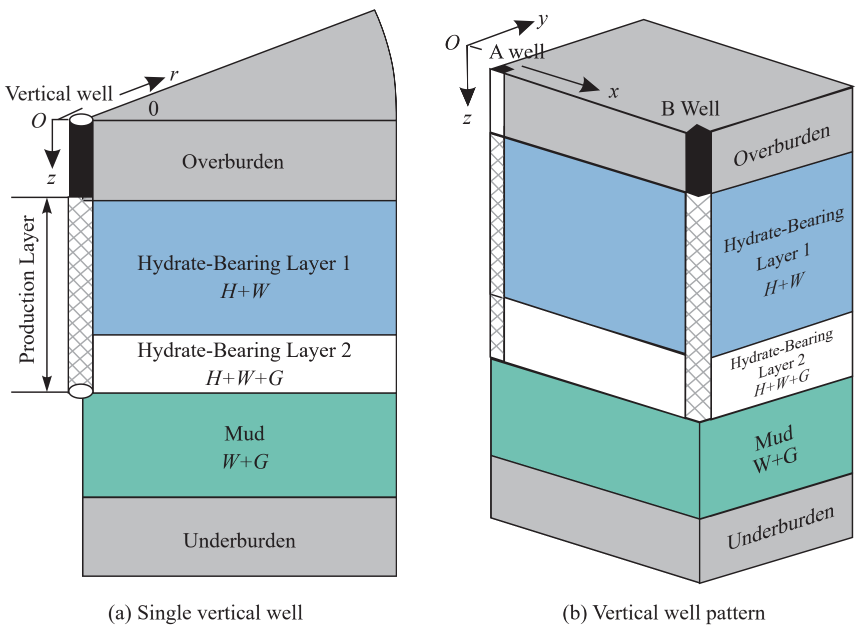

Fig. 5. Schematic diagram for a numerical simulation model of depressurization exploitation of hydrate reservoir at W17 station (modified from Chen CY et al., 2020).

depressurization combined heat injection, Yang H et al. (2012) proposed a novel approach for producing gas from marine natural gas hydrate reservoirs by combining ocean surface warm water flooding and depressurization (Fig. 6). Warm water from the ocean surface was injected Through well into the gas hydrate formation, to facilitate gas production in second well by depressurization. The gas production of the single depressurization technique dwindles over time, while utilizing the combined production technique extensively prolongs the duration of high production rates, enhances productivity, and curtails geological risks caused by formation deformation. Loh M et al. (2015) experimentally investigated the stimulation effect under the dual vertical wells composed of one depressurization and heating wells. Their findings indicate that integrating depressurization and heating methods enhances the recovery rate by 5% and the net energy by nearly 10%, compared to exploitation by the single vertical well.

The above demonstrates that dual vertical wells with depressurization can significantly increase the production of a single well. Additionally, dual vertical wells with combined depressurization and heat injection can increase the period of stabilized production. Therefore, studying the effect of the distance between two wells on gas production is necessary to increase cumulative gas production further.

4.2.2. Two horizontal wells

In current research on double horizontal wells, two

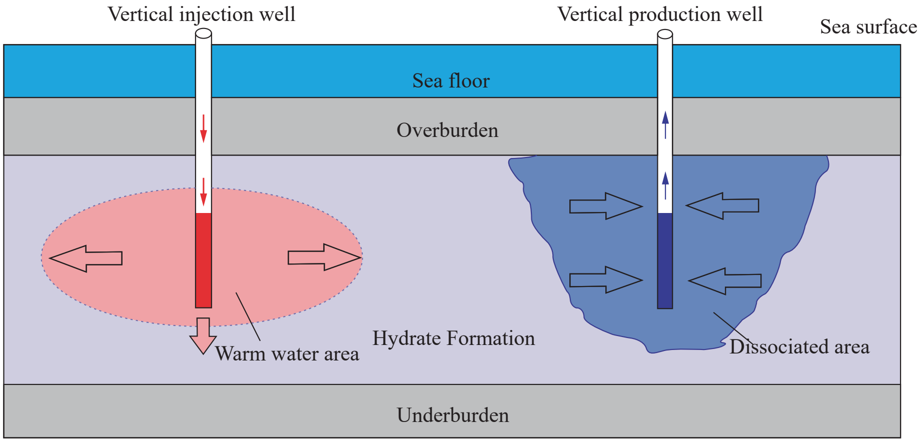

Fig. 6. Schematic diagram of gas hydrate exploitation by the combination of ocean surface warm water injection with depressurization (modified from Yang H et al., 2012).

horizontal wells are typically placed at the top and bottom of a hydrate layer, respectively. Heat injection is used in one well, while depressurization is used in the other for production. This is known as dual horizontal well heat injection combined with depressurization production. Sasaki K et al. (2009, 2010) proposed a dual-horizontal well hot-water injection gas production system. The two horizontal wells are spaced 3 m to 5 m apart. The lower well is injected with hot water at a temperature of 120°C, while the upper well is depressurized. Results from the experiments indicate that gas production during intermittent hot water injection is higher than during continuous hot water injection. Conversely, gas production during rest stages is lower than during continuous hot water injection stages. The numerical simulation results indicate that intermittent hot water injection produces about 80% of the gas production of continuous hot water injection, and the water production of intermittent hot water injection is only half that of continuous hot water injection. Therefore, intermittent hot water injection was found to be more economically efficient than continuous injection. Moridis GJ et al. (2009, 2011) simulated the design scheme of parallel horizontal well using data from block 818 in Alaminos Canyon, Gulf of Mexico (Boswell R et al., 2009). The design comprises two parallel horizontal wells (Fig. 7), which resemble the inverted SAGD (steam-assisted gravity drainage) structure. In the production of two horizontal wells, pyrolysis separation is the main process in the first stage, and pressure reduction is the main process in the later stage. When the pressure of the upper horizontal well is lower than 0.8 times the formation pressure, effective decomposition can occur, resulting in higher gas production (for 1000 m long horizontal wells, up to 2.2×10^6 STm^3/day = 76 MMSCFD) (Moridis GJ and Reagan MT, 2011). Feng JC et al. (2015) proposed a method for combined production of double horizontal wells with depressurization and hot water injection based on hydrate measurement data in the South China Sea. The gas production well is placed above the water injection well. The authors assert that a higher injection temperature will result in a shorter duration of gas production and a higher rate of hydrate decomposition. Consequently, optimizing the approximate injection water temperature is crucial to hydrate decomposition. Li B et al. (2016) systematically investigated the gas production characteristics of double horizontal wells by experiments and numerical simulations. The two production wells are situated on the same vertical plane, which contains one upper injection well and one lower production well. Their findings suggest that hot water flows more readily downward under gravity. However, to counteract heat loss, it is necessary to raise the temperature around the injection well to more than 78.0°C. The author concludes that double horizontal wells may well have commercial potential.

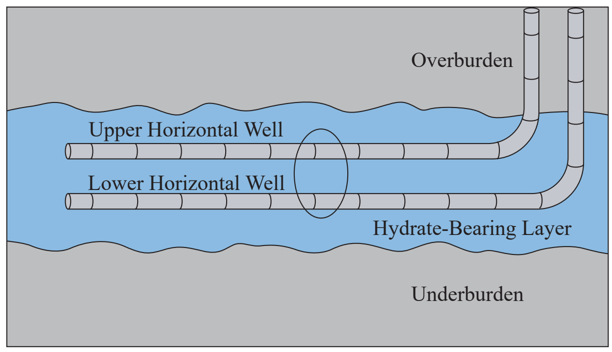

Fig. 7. Two-well design for gas production (modified from Sasaki K et al., 2009).

The aforementioned studies demonstrate that the productivity of combined depressurization and heat injection exploitation using two horizontal wells is significantly enhanced compared to depressurization exploitation using a single horizontal well. Nevertheless, a comprehensive analysis based on geological conditions is required to determine whether the heat injection well should be supplemented.

4.3. Multi-branch well scheme

Multi-branch wells are typical representatives of complex structural wells, which can increase the production of a single well and reduce the cost, and the technology is relatively mature and widely used in developing various oil and gas reservoirs (Yang L et al., 2019). The research on multi-branch wells in hydrates is just beginning, and the research is mainly limited to a single reservoir, which is ideal. Multi-branch wells are wells with two or more wells drilled in a main well. Multi-branch wells are primarily vertical multi-branch wells and horizontal multi-branch wells. Vertical multi-branch wells are drilled with multiple ultra-short radius branches in a vertical section, also called spiral multi-branch, and are commonly used in single thick reservoirs. Horizontal multi-branch wells, also known as multi-bottom wells or horizontal multi-branch wells, are more suitable for use in multi-layered reservoirs.

Regarding multi-branch well depressurization combined heat injection, Liu YG et al. (2019) propose a novel approach of utilizing geothermal energy to exploit gas hydrates (geothermal energy and natural gas, GEAN) The well cluster model is composed of a horizontal well 1 located in the geothermal reservoir, as well as well 2 with two branches at the top and bottom hydrate layer (Fig. 8). Compared to the depressurization method, the GEAN method resulted in a 63.9% increase in cumulative gas production. The higher geothermal reservoir temperature, higher geothermal gradient, and better heat transfer performance of HBL make it a favorable method.

Currently, many scholars have focused on the study of well placement and the exploitation effect of multi-branching wells under the condition of depressurized exploitation. Zhang PP et al. (2022, 2021) established a numerical model of depressurized exploitation of vertical branching wells based on the geologic data from the SH7 measurement point in the South China Sea. It was concluded that reservoir anisotropy favors improved pressure propagation mode, which significantly improves recovery rate and gas production duration. Hydrate aggregation without impermeable boundaries is difficult to extract commercially. Ye HY et al. (2021, 2022) investigated the production capacity of complex structured wells for marine gas hydrates by establishing a numerical model of multi-branching wells based on the data of the first test production in the South China Sea Trough, Japan. The study shows that compared with single wells, multi-branch vertical wells, multi-branch horizontal wells, and cluster multi-branch wells can increase production capacity to a certain extent. Complex structure wells can significantly increase the decomposed area, especially cluster wells, whose capacity can be increased by 54.36%–250.66% compared with single wells. With the same pressure drop, complex structure wells exploit natural gas hydrate with more hydrate decomposed, better gas production and longer gas production time (Fig. 9). Wang FF et al. (2023) used a multi-field coupling method to establish a natural gas hydrate horizontal well downhole gas production model, and investigated the effects of horizontal well length, horizontal well diameter, and the number of horizontal wells on the production of natural gas hydrate. It is concluded that with the increase of horizontal well length, the decomposition rate of gas hydrate is accelerated, and the maximum gas production occurs earlier; with the increase of horizontal well diameter, the initial gas production increases significantly. Mao PX et al. (2021) established a numerical model of three types of hydrate reservoirs in Site W11 of Shenhu in the South China Sea and simulated the effect of branch horizontal well configuration and deployment location on production. The study concluded that the optimal location of horizontal

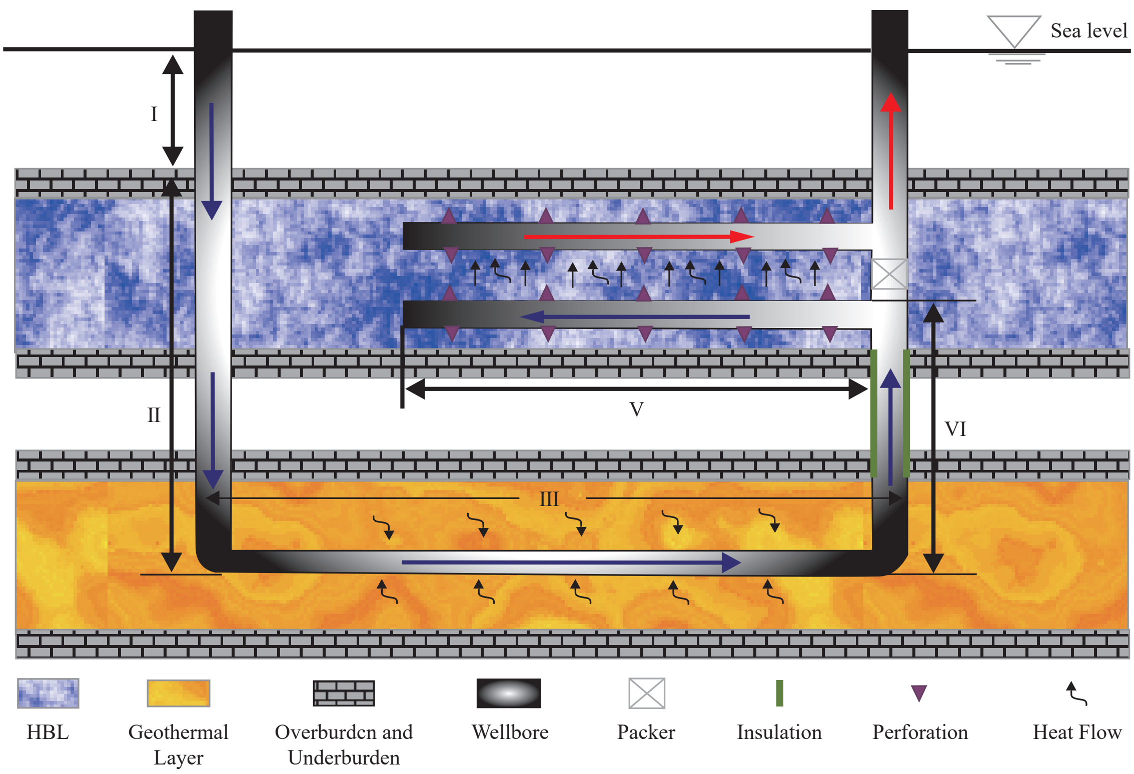

Fig. 8. Schematic diagram of GEAN (modified from Liu YG et al., 2019).

branching is in the lower part of the reservoir, and the gas production of spiral four-branch horizontal wells is higher in low-permeability hydrate reservoirs. Mao PX et al. (2023) also proposed a production enhancement strategy combining multi-fracture and multi-branching wells, i.e., multi-fracture and multi-branching wells. By increasing the number of fractures and the width of the seam spacing and other multi-faceted fractures, the reservoir volume was significantly increased, and the production was increased by more than 23 times, which greatly improved the decomposition rate and production efficiency of the hydrate reservoir.

The common feature of multi-branch wells is that the synergistic interference of the branches is conducive to increased productivity, and the greater the number of branch wells and the greater the branch length, the greater the increase in production. Increasing the volume of the fracture has a more significant impact on increasing production. Therefore, it is expected that multi-branch well depressurization and joint fracturing is a kind of production enhancement measure to increase the production of a single well significantly.

4.4. Multi-well scheme

The multi-well scheme is expected to be a new method for commercial exploitation of natural gas hydrate in offshore areas in the future. Increasing well numbers, deepening comprehension, and refining the degree of exploitation characterize the progression from oil and gas field exploration to development. Most wells adopt a single-well system during the initial exploration and development phases. After thorough development, a multi-well system consisting of various well configurations can be gradually established. The layout of the multi-well system comprises mainly area patterns and row patterns (Fig. 10). At present, the production test of the hydrate reservoir is ongoing. The study on single and double-well systems has been extensively studied, and the feasibility and effectiveness of multi-well systems are currently being explored. These studies provide a scientific basis for future commercial developments.

4.4.1. Well Network

Well pattern refers to the spacing pattern of injection wells and production wells in the development process, including number of wells, well category, well spacing pattern and well spacing. Well pattern optimization mainly aims to determine the reasonable matching relationship between well pattern parameters and reservoir parameters; it is the core content of development plan design and is directly related to production, recovery factor and economic benefit. The public data show that the well patterns implemented in hydrate exploitation include five-spot pattern, seven-spot pattern and nine-spot pattern.

The five-spot well pattern is an area pattern comprising one injection well and four production wells. Upon analyzing the injection-production units, one injection well corresponds to one production well, with an injection-production well ratio of 1∶1. The five-spot pattern is a straightforward method due to its high injection-production intensity, effective development, and relatively high recovery rate. The ratio of injection-production wells utilizing the reverse seven-point pattern is 1∶2, making it appropriate for irregular reservoirs with small areas and developed faults. During development, the reverse nine-point area well pattern, with a ratio of

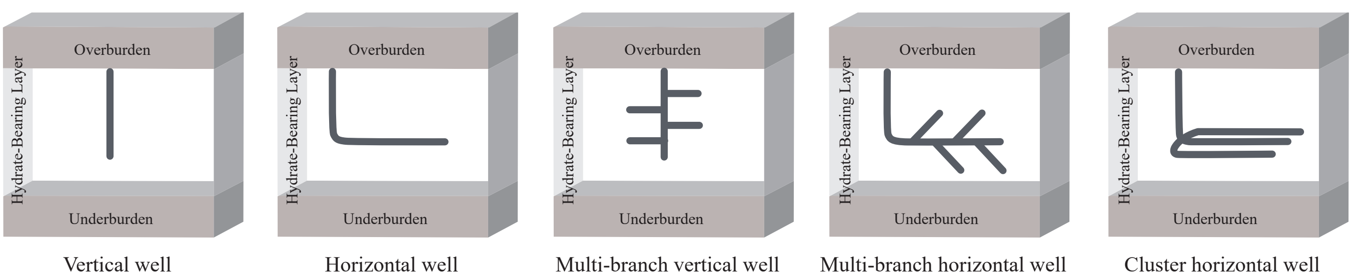

Fig. 9. Design cases of various well types (after Ye HY et al., 2022).

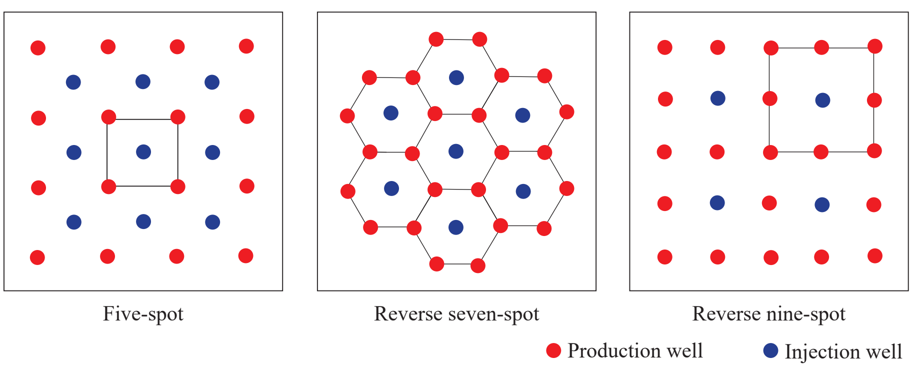

Fig. 10. Schematic top view of the well patterns.

injection-production wells of 1∶3, is typically adopted in the early stages due to a limited understanding of reservoir distribution. It can utilize the benefits of multiple production wells to produce more oil and gas and deepen the understanding of the reservoir utilization status. According to the geological parameters of the hydrate reservoir in the Shenhu area of the South China Sea, Yu T et al. (2020) established a three-dimensional reservoir model and compared the effects of depressurization and heat injection in multiple well systems. Four production systems were designed, including a single-well system, a two-well system, a three-well system, and a four-well system. Numerical simulation indicates that the dual well system performs best in low permeability reservoirs, although gas production potential declines as the number of wells increases. This is primarily due to an inter-well retention zone, which may lead to the secondary formation of hydrate. Therefore, late heat injection is thought to decrease the chance of hydrate secondary formation. The four-well system for depressurized production comprises one well of hot water injection and three wells of depressurization, forming an injection production unit of inverted nine-point pattern (Fig. 11). After 10 years of depressurization production, the total amount of natural gas rose by 31.9%, compared with 20 years of depressurization. The hot water injection method can potentially remove the blind zone and increase the recovery rate of low permeability hydrate reserves.

Sasaki K et al. (2010) designed four pairs of double horizontal wells in the Nankai Trough of Japan to form a water drive well pattern with equal numbers of injection and production wells, based on previous studies on methane hydrate production by hot water injection in double horizontal wells (Sasaki K et al., 2009). Four double horizontal wells were preheated by hot water circulation for 90 days so that the areas between the two horizontal wells were connected vertically (Fig. 12). Four pairs of wells were connected, and gas was produced for one year. The reservoir's horizontal section was expanded using radial hot water flow. Numerical simulation results indicate that radial hot water flow between horizontal well pairs increase daily gas production to approximately 1.3×10^8 STD-m^3/d over 15 years.

Moridis GJ and Kowalsky M. (2006) conducted simulations for Class 2 hydrate reservoirs without a trap by a single vertical well and a five-point well pattern (Fig. 13). The results indicate that both production methods have limited gas production, which is significantly less than the total amount of methane released from the hydrate decomposition. Additionally, it is challenging to recover the gas generated by hydrate decomposition in the five-spot pattern due to the absence of a trap layer.

Wang Y et al. (2013) used the Cubic Hydrate Simulator (CHS) to investigate depressurization production (DP), heat injection (HS-5S), and combined heat injection and depressurization (H&D-5S) for hydrate decomposition. Their analysis suggests that the H&D-5S method can effectively decompose almost all hydrates in the reservoir. The H&D-5S method, which combines heat injection and pressure

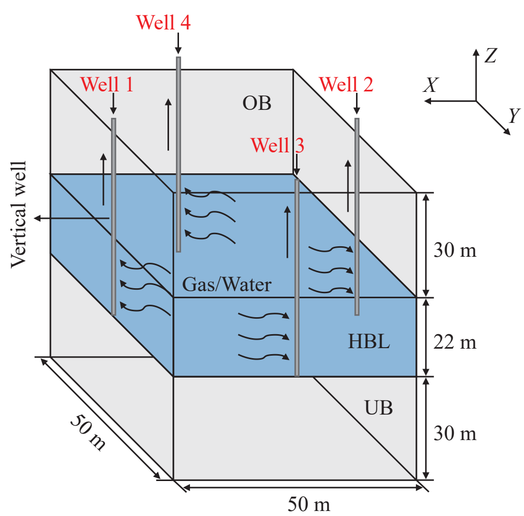

Fig. 11. Reverse nine-point well pattern (modified from Yu T, 2020).

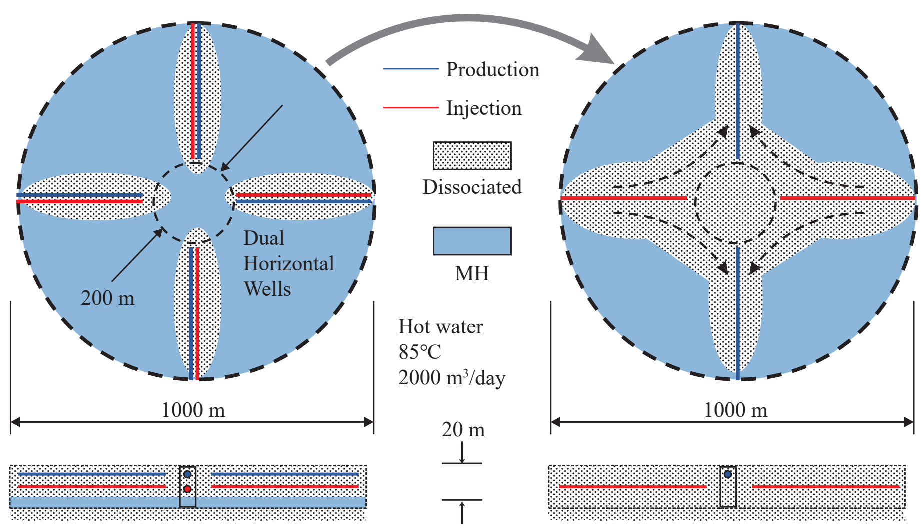

Fig. 12. Numerical model for field production scheme using four pairs of dual horizontal wells in radian arrangement (modified from Sasaki K et al., 2010).

reduction, is the optimal approach for hydrate exploitation. This method can result in the highest gas production rate and shortest production time. Wang Y et al. (2014) developed A new hydrate exploitation method of five-point thermal huff and puff method (HP-5S), which combines the five-point well pattern of thermal huff and puff with depressurization, can bring high recovery efficacy for hydrate exploitation.

Sun ZX et al. (2020) conducted a production simulation of CO_2 replacement hydrate based on the field test data of natural gas hydrate in Shenhu, South China Sea. According to the simulation results, there were significant implications for hydrate exploitation: the cumulative methane gas production of the nine-point well pattern exceeds that of the five-point and seven-point well patterns; enhanced methane cumulative production, CO_2 storage rate, and replacement rate are facilitated by larger well spacing; initial hydrate saturation significantly affects cumulative methane gas production; the hydrate is initially replaced at the top due to the lower density of CO_2 as compared to water.

Zhang YT et al. (2023) established a numerical model of three horizontal wells with depressurization, heat injection, and inhibitor injection, viz, using the deployment of production wells on both sides of the middle injection wells as an example of hydrate at Station SH7, Shenhu, South China Sea, and compared the results, which showed that the injection of hot methanol solution can increase the temperature of the reservoir and promote the decomposition of hydrate, which improves the inadequacy of a single depressurization and hot water injection method and has a higher effect of hydrate decomposition.

The above results show that the shape of the well network and the production method form a complete injection and production system. The core content of the development plan design is the study of the optimal combination of different well network forms and different extraction methods (injection and production well network optimization).

4.4.2. Multiple Well Groups

Some scholars have proposed the Well Group Design Scheme to rapidly achieve industrial production capacity within a short timeframe, considering the unique environment of marine hydrates. Following the second test production of hydrate, the MH21 Research Consortium (Japan) proposed a new multi-well system (Fig. 14) designed for medium-scale production. The system includes an offshore platform and two groups of multi-vertical well systems. With 12 wells in each group and 24 wells in the entire production system, the estimated recoverable methane in the area can reach 8.0×10^9 standard cubic meters based on an assumption of 100 m reservoir thickness. The average gas production for 15 years is approximately 6.0×104 cubic meters per day, considerably higher than the current field test results of a single vertical well in the South China Sea (2.9×10^3 to 2.0×10^4 m^3 per day).

Scholars have designed various cluster schemes for gas hydrate in the Krishna-Godavari Basin, India. They have also analyzed the technical and economic feasibility of multi-well depressed-pressure development. For instance, Deepak M et al. (2019) designed 20 production clusters with six wells based on data from the NGHP-02-16 site in the Krishna-Godavari Basin, India. The model includes a total of 120 wells. The objective of the design is to produce 6 MMSCMD (Million Standard Cubic Meters per Day) of gas per day for 30 years, which is economically viable at a natural gas price of $9/MMBtu. Vedachalam N et al. (2020) further analyzed the hydrate reservoirs in the Krishna-Godavari Basin, India. The study findings indicate that 20 wells yield 3.6-year investment returns at a hydrate saturation of 90% for reservoirs with a permeability of 200 mD, while 40 wells can bring the same investment returns at a saturation of 75%.

Ma XL et al. (2021) designed horizontal well groups for hydrate reservoirs in the South China Sea as shown in Fig. 15. All horizontal wells are located at the same depth within the hydrate reservoirs and have the same trajectory direction. Adjacent horizontal wells are spaced 80 m apart, controlling a production area of 40 m on both sides of a single horizontal well, which provides a design scheme for the future numerical simulation study.

Currently, the design of well groups is still in the conceptual stage. In the future, the multi-well cluster exploration method should be optimized for the actual gas

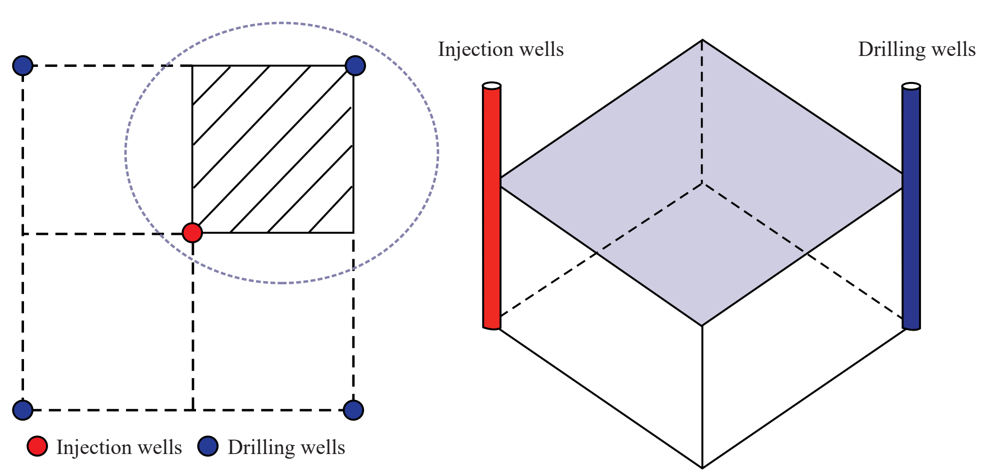

Fig. 13. Schematic diagram of five-point pattern method (modified from Moridis GJ and Kowalsky M 2006).

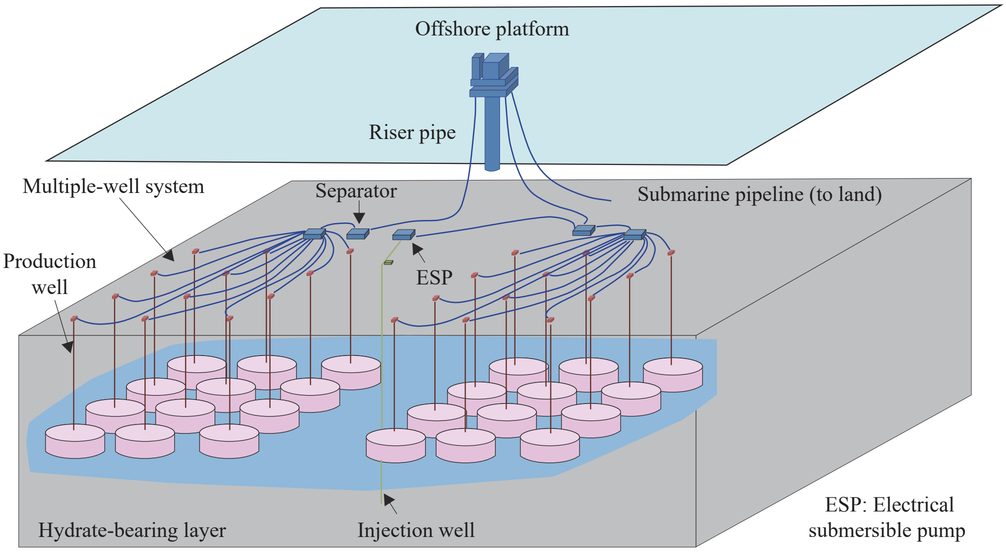

Fig. 14. Schematic diagram of multiple-well systems used for offshore methane hydrate production (modified from MH21 Research Consortium, 2017).

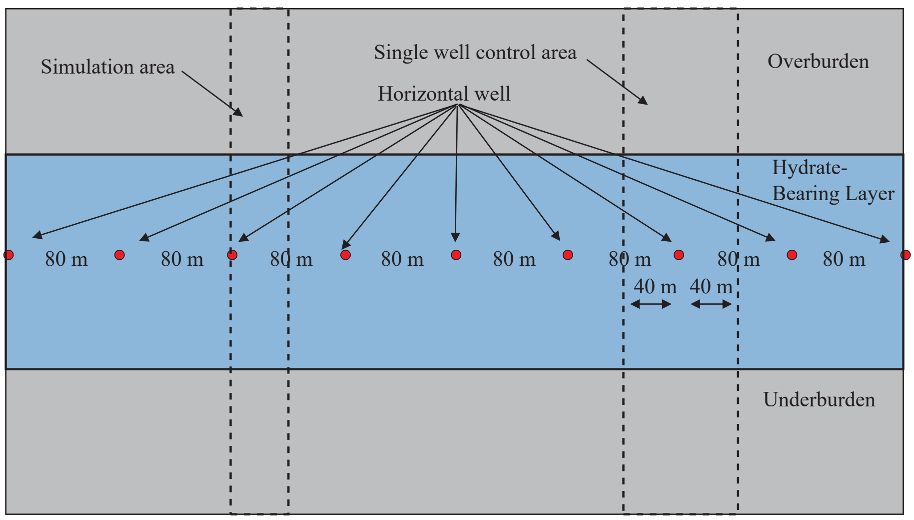

Fig. 15. Schematic diagram for exploitation of argillaceous siltstone hydrate reservoir by horizontal well group (modified from Ma XL et al., 2021).

hydrate reservoir, and the best well pattern should be designed to fully utilize the synergistic effect of multiple wells to promote the long-term economic and effective development of hydrate.

5. Discussion on well-pattern methods

The aforementioned studies suggest that the well pattern directly impacts gas production. The design of well types and patterns for gas hydrate exploitation, whether for single or multiple wells, is closely associated with reservoir geological conditions, production conditions, and economic benefits (Table 3).

5.1. Application conditions of different well types

Vertical wells are one of the most basic types of wells. Vertical wells can penetrate multiple reservoir layers and are more suitable for single or multi-layered, thick and highly permeable reservoirs. Vertical wells have a lower technological threshold and operating costs. However, it has the disadvantage of limited drainage area near the wellbore, which leads to localized degradation of nearby gas hydrates.

Directional wells are appropriate for geological settings with complex conditions, such as fault barriers, structural inclinations, discontinuous vertical reservoir distribution, and limited surface conditions. The contact area between a directional well and the reservoir is greater than that between a vertical well and the reservoir, which generally results in intermediate gas production between the production of vertical wells and horizontal wells when directional wells are employed.

Horizontal wells are more effective in thin formations with stable lateral reservoir distributions. In these hydrate reservoirs with thin layers, horizontal wells can produce more methane than vertical wells can. The longer the horizontal sections of horizontal wells, the greater their contact area with

Table 3. Comparison of applicable conditions for various well patterns.

Scheme	Well-Type	Geological Conditions	Advantages	Disadvantages	Examples	References
Single well	Vertical well	Thick reservoirs with relatively good properties and multiple vertical layers.	(1) Passing through multiple strata in the vertical direction, with high initial production from a single well during depressurization. (2) Low investment per well.	A small decomposing area near the wellbore.	Class 1 and Class 2 hydrates in the Mackenzie Delta, Canada.	Moridis GJ et al., 2007a Li SX et al., 2018
	Horizontal well	Relatively thin and homogeneous reservoirs with fewer vertical layers.	The high contact area between the horizontal well and the reservoir. Gas production is more than three times that of vertical wells.	High investment for a single well.	Class 2 hydrates in the Nankai Trough, Japan, and Class 3 hydrates in the South China Sea, China.	Moridis GJ et al., 2007b Feng YC et al., 2019 Li SX et al., 2020
	Directional well	The formation has a certain dip angle but a stable planar distribution and poor vertical continuity.	High gas production, more than 1.2 times that of a vertical well.	Relatively high investment costs, between those of vertical and horizontal wells.	Class 2 and 3 hydrates in the North Slope of Alaska, USA.	Myshakin EM et al., 2016
Dual Wells	Dual vertical well	Vertically developed Multiple layers.	High Gas production from depressurization recovery is twice that of a single vertical well.	Easily leading to well interference that can negatively affect production.	Class 2 hydrates in the Nankai Trough, Japan, and Class I hydrates in the South China Sea, China.	Yu Tao et al., 2019 Chen CY et al., 2020 Yang H et al., 2012 Loh M et al., 2015
	Dual horizontal well	Stable reservoir distribution.	The heat injection method is higher than that of depressurization.	High heat loss	Class 2 and 3 hydrate reservoirs in the Alaminos Canyon 818 area in the Gulf of Mexico.	Sasaki K et al., 2009 Moridis GJ et al., 2009; 2011 Feng JC et al., 2015 Liu YG et al., 2019
Multi-branch well	Vertical multi-branch well	The reservoir has a large single layer thickness, and multiple short branches are drilled in the same layer.	Initial single-well production is high. For anisotropic reservoirs, the duration of gas production can be significantly increased.	The interface is technically required where the main borehole meets the branch boreholes.	Class 3 hydrates in the South China Sea	Yang L al., 2019 Zhang PP et al., 2022; 2021 Mao PX et al., 2021; 2023
	Horizontal multi-branch well	In the longitudinal direction, there are several reservoirs, and the layers are more certain compartments. Horizontal branches are drilled in different layers or in the upper and lower parts of a single layer with a large thickness.	It can realize the multi-layer and three-dimensional development of one well, the full decomposition of hydrate reservoirs, a substantial increase in production, and a reduction of investment costs.	The wells are structurally complex and difficult to drill.	Class 3 hydrates in the South China Sea, Class 3 hydrates in Japan	Liu YG al., 2019 Ye HY et al., 2021; 2022
Multiple Wells	Well Network	(1) Stable reservoir distribution and good connectivity suitable for the reverse nine-point method. (2) Hydrate reservoirs in the presence of small area faults suitable for The Reverse Seven Point Method. (3) Reservoirs undergoing significant changes suitable for The Five-Point Method.	Eliminating the blind zone caused by secondary hydrate formation via depressurizing and injecting hot water.	Multiple adjustments to the well network in the later stages due to inadequate reservoir understanding in the early stages.	Class 3 hydrates in the South China Sea, China.	Sasaki K et al., 2009 Yu T et al., 2020
	Well Groups	Complex geological conditions with large dip angles and susceptibility to directional drift, such as in marine environments.	Higher gas production and lower development costs.	The limited space on platforms and the challenging ocean conditions, including wind and waves, for	Class 2 hydrates in the Nankai Trough, Japan.	Moridis GJ et al., 2019 Vedachalam N et al., 2020 Ma XL et al., 2021

the reservoir, thereby increasing gas production. In unconsolidated formations, horizontal wells can produce less sand than vertical wells.

Multi-branch wells are more adaptable and can be designed flexibly according to the reservoir structure and ground conditions. For thick reservoirs, they can be designed as vertical multi-branch wells, for multi-layered reservoirs, they can be designed as horizontal multi-branch wells, and for special ground conditions, they can be designed as directional multi-branch wells. The process of multi-branch wells is relatively complicated, to facilitate the inclination of drilling, there must be a certain distance between the upper and lower branches, and it is not easy to use multi-branch wells for the case of shallow burial and the distance between two reservoirs is relatively close.

From the results of short-term field tests and long-term numerical simulations, it is clear that for type 1 hydrates, at the interface between the hydrate layer and the free gas layer, a small change in pressure and temperature can induce hydrate separation, and therefore both vertical and horizontal wells are relatively good for depressurization (Moridis GJ et al., 2007a, 2007b). For class 2 hydrates, vertical wells are preferred for pressure relief due to a water layer in the lower part of the hydrate layer, which is less compressible (Moridis GJ and Kowalsky M, 2006). In contrast, Class 3 hydrates are relatively ineffective when exploited by vertical-well drilling. When horizontal wells are used, gas production from downhole hydrate production increases significantly compared to class 1 hydrate production for both class 2 and 3 hydrates. Typically, the gas production of horizontal wells is more than three times that of vertical wells, and the gas production of directional wells is more than 1.2 times that of vertical wells (Moridis GJ et al., 2007a, 2007b; Feng YC et al., 2019). Analysis of the exploitation characteristics of various types of multi-branch hydrate wells shows that their gas production is several times higher than that of horizontal wells, which mainly depends on the length of the branch wells, the number of branches, and fractures (Ye HY et al., 2022; Mao PX et al., 2023).

It can be seen that it is difficult to meet the demand for industrialized natural gas hydrate exploitation by single vertical wells and horizontal wells. Complex structure wells, represented by multi-branch wells, have the technical advantages of flexible design and multi-layered and three-dimensional development and are expected to play an irreplaceable role in future natural gas hydrate industrialization (Wu NY et al., 2020).

5.2. Adaptability analysis of well network and well group

The principle of deploying well networks and well groups is to adapt to reservoir distribution, control more reserves, and achieve the designed production capacity. To prevent secondary hydrate formation in the retention zone between multiple wells with depressurization, various configurations of injection-production well networks, including heat injection and displacement, have been investigated (Yu T et al., 2020).

There are three commonly used well network configurations: the reverse nine-spot, the reverse seven-spot, and the five-spot well pattern. The reverse nine-spot technique is appropriate for reservoirs with stable distribution and good connectivity. The technique allows for a high control over the reservoir, but it requires continuous adjustment due to the influence of reservoir heterogeneity. The reverse seven-spot technique is appropriate for blocks with developed faults and small areas. One advantage of this method is that the geometric shape of the reservoir does not restrict the well network. However, adjusting the well network during later stages poses a challenge. The five-spot well pattern is appropriate for reservoirs with significant variations. Although the average single-well production is high, the total water produced is also high. In the initial stages of development, the reverse nine-spot technique is commonly adopted due to limited knowledge of the reservoir, then switched to the five-spot approach later if the reservoir changes. Regarding well network research, some scholars have conducted indoor experimental and numerical simulation studies. According to the experimental study of cubic hydrate simulator (CHS), the best recovery rate can be obtained by using five-point well network depressurization combined with heat injection for hydrate exploitation (Wang Y et al., 2013, 2014; Li G et al., 2014). Numerical simulation studies concluded that reverse nine-point network depressurization followed by heat injection can prevent the formation of secondary hydrates in the reservoir and significantly increase the cumulative gas production from three types of low-permeability hydrate reservoirs (Yu T et al., 2020). In CO_2 replacement method, the reverse 9-point method has a larger swath area, higher cumulative methane production, and CO_2 storage efficiency compared with the reverse 7-point and 5-point well networks (Sun ZX et al., 2020).

Well-groups are supposedly suitable for complex geological conditions with large dip angles and orientation drift. The advantage of well groups lies in their capacity to drill as many wells as possible in the same field or platform, facilitating centralized station construction and management, saving space, and then reducing development costs. However, adjusting the well network during later stages is difficult, posing challenges in operation and construction and uplifting development costs.

In the future hydrate exploitation process, to adapt to the reservoir's geological conditions and the special characteristics of offshore operations, it is necessary to optimize the design of different platforms with different well types, well networks, and exploitation methods so as to achieve safe and efficient gas production.

6. Conclusions

In recent years, significant advancements have been made in understanding the reservoir occurrence, distribution, and characteristics of natural gas hydrate through laboratory research and field production testing (Wu NY et al., 2020). Numerous well-designed methods have been developed for different types of hydrates. By summarizing and analyzing the current cases of development, the following conclusions can be drawn:

(i) The selection of a well type suitable for hydrate production must take into account the reservoir type, reservoir properties, and recovery methods. Vertical wells with simple well types and low drilling costs have been extensively utilized in l, 2, and 3 hydrate test productions worldwide. However, laboratory experiments and numerical simulations indicate that horizontal well production is more efficient than vertical well production. Recent tests in China have confirmed that depressurization of horizontal wells can significantly enhance single-well production.

(ii) The selection of the well pattern depends on both hydrate productivity and the expected economic benefits, including anticipated production levels and associated input costs. However, the estimated recovery rate is influenced by geological conditions, hydrate composition, and well configuration. Therefore, there is no universally optimal well design.

(iii) The exploitation method chosen greatly influences the well pattern. Single-well depressurization and heat injection methods have very limited effectiveness. Multi-well combined exploitation methods, such as depressurization coupled with heat injection or displacement, offer distinct advantages.

(iv) Future hydrate development will focus on integrating well type, well pattern, and exploitation method. For different types of hydrate reservoirs, innovative multi-well production patterns will be developed. Additionally, the concept of a “well factory” — involving group well design and centralized construction — will be explored to significantly increase single-well production and recovery rates, reduce development costs, and enable the commercial exploitation of natural gas hydrate resources.

CRediT authorship contribution statement

Hai-long Lu conceived the research idea, Lang-feng Mu wrote the original draft, Haotian Liu contributed to the discussion, Chi Zhang collected the data, and Yi Zhang edited the geological map. All authors provided feedback on the research, analysis, and manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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