

Article

Stimulation Behavior of Fracture Networks in the Second Hydrate Trial Production Area of China Considering the Presence of Multiple Layers

Chen Chen ^{1,2} , Xitong Li ^{1,2}  and Xiuping Zhong ^{1,2,*} 

¹ College of Construction Engineering, Jilin University, Changchun 130026, China; chenchen@jlu.edu.cn (C.C.); lixt17@mails.jlu.edu.cn (X.L.)

² Key Laboratory of Drilling and Exploitation Technology in Complex Conditions, Ministry of Natural Resources, Changchun 130026, China

* Correspondence: zhongxp0189@jlu.edu.cn

Abstract: The fracture network's stimulation of China's second hydrate trial production area was investigated. First, the stimulation potential of the fracture network and the influence of well arrangement on hydrate development were explored. Second, the fracture distributions' influence on development behavior was investigated. Results showed that the fracture network could cause the trial production reservoir to reach the commercial production rate. The average CH₄ production rate of unit horizontal well length using the depressurization method and depressurization combined with thermal stimulation (combined method) were 61.3 and 151.5 m³/d with the fracture network and 23.7 and 14.3 m³/d without the fracture network. In addition, without the fracture network, the development behavior of wells arranged in the mixed layer was better than that of wells arranged in the hydrate layer. However, with the fracture network, the result was reversed. With the depressurization method, the best production behavior was obtained by fracturing in the hydrate layer; however, for the combined method, the best production behavior was obtained by fracturing in the hydrate and mixed layer, while fracturing in the free gas layer was useless. This study provides a valuable reference for the hydrate development of China's trial production reservoir.

Keywords: natural gas hydrate; trial production of China; multi-layer; fracture network; stimulation behavior



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1. Introduction

Natural gas hydrate (NGH) occurs widely in permafrost and marine sediments [1]. The carbon content of CH₄ in global NGH is estimated to be twice that of all fossil fuels [2,3]. Due to its huge reserves, high energy density, and cleanness, NGH is considered a promising form of alternative energy in the 21st century. The governments of China, Japan, the United States, and India have attached great importance to hydrate exploitation [4–9].

The NGH reservoir in the South China Sea is the most promising one in China, where the prospective resource is predicted to be equivalent to 74.4 billion tons of oil [10,11]. China has carried out several drilling and exploration works in this area and implemented two trial production projects in 2017 and 2020. In particular, the second trial production created two world records for gas production rate and cumulative gas production of 2.87×10^4 m³/d and 8.614×10^5 m³, respectively [9]. However, one of the remarkable characteristics of the trial production reservoir is that the effective permeability of the reservoir is extremely low. Such low permeability brings serious challenges to the proposed development methods, including depressurization, thermal stimulation, and gas replacement [12–15]. Ma et al. [16] and Yu et al. [17] simulated the depressurization's production behavior in the trial exploitation reservoir by horizontal well. Their results showed that the CH₄ production rate per unit of horizontal well section was less than 10 m³/d, and

the hydrate dissociation area's radius was only about 20m. This production behavior is far less than commercial standards. Therefore, appropriate stimulation technologies may be necessary for hydrate reservoirs in the South China Sea.

Multi-stage fracturing of the horizontal well is the essential technology to realize commercial exploitation of unconventional gas reservoirs with low and ultra-low permeability. The research on hydraulic fracturing in hydrate reservoir development has been a hot topic recently. Too et al. [18,19] and Konno et al. [20] studied the mechanical response of sand-bearing hydrate sediments during hydraulic fracturing. Their results proved that CH₄ hydrate-bearing sand can be fractured. Zhang et al. [21] conducted hydraulic fracturing experiments on artificially prepared permafrost-like hydrate-bearing sediment samples. The results showed that complex fractures appeared when high-viscosity fracturing fluid was used. Yao et al. [22] numerically studied the mechanical response of hydrate-bearing sediments during hydraulic fracturing by the discrete element method. The results showed that multiple main fractures were obtained when the hydrate saturation was 40–60%. The above results preliminarily proved that hydrate-bearing sediments have artificial fracability. Chen et al. [23,24], Feng et al. [25], and Sun et al. [26] numerically studied the effects of hydraulic fractures' stimulation behavior on depressurization development. Results showed that the hydraulic fractures significantly promoted the pressure relief of the reservoir and significantly promoted hydrate decomposition and gas production. Zhong et al. and Chen et al. [27,28] studied hydraulic fractures' stimulation of depressurization combined with hot water injection. The results showed that hydraulic fractures greatly promoted the migration of injected thermal fluid and methane between the injection and production wells. As a result, hydrate decomposition and methane production were greatly improved, and the effective spacing of the well pattern was expanded. However, in the trial production area of China, simple hydraulic fractures showed poor stimulation potential. Ma et al. [16] numerically studied the stimulation potential of horizontal fractures by using the depressurization method to develop the reservoir in the China trial production area. The results showed that the methane production rate of the unit horizontal well section was only 16 m³/d, and fracture length had little effect on production behavior. Yu et al. [29] numerically studied the stimulation potential of a single horizontal fracture combined with multiple branch fractures using the depressurization method to develop the hydrate reservoir in China's trial production area. Results determined that the CH₄ production rate per unit horizontal well section was only about 15 m³/d, and the production behavior was insensitive to the changes in fracture parameters. These results proved that the simple fractures have little stimulation effect on the Shenhu trial production reservoir. Our previous study determined that the fracture network significantly improved fluid migration, hydrate dissociation, and CH₄ production capacity, proving that the fracture network has great stimulation potential for low-permeability hydrate reservoir exploitation [30,31]. Therefore, it is necessary to explore the stimulation potential of fracture network on the development of the hydrate reservoir in China's trial production area.

Moreover, another remarkable characteristic of China's trial production reservoir is a mixed phase layer and free gas layer underlying the hydrate layer [32]. Such reservoir characteristics result in methane production capacity being sensitive to the production wells' arrangement. Ye et al. [9] pointed out that for the depressurization method, the production wells should be arranged in the mixed layer, to strengthen the transmission of pressure dropping through the mixed layer, meanwhile achieving full recovery of the methane in the free gas layer. This well layout yielded high CH₄ production in short-term trial production. However, in long-term production and after network fracturing, it should be further clarified which layer the well is arranged on for the best production behavior, as this information is crucial to the drilling design. Furthermore, the presence of multiple layers makes the production behavior different with fracture distribution in different layers; thus, it is important for fracturing design to clarify the influence of fracture distribution on production performance. Therefore, considering the presence of multiple

layers, investigating the stimulation behavior of the fracture network on China's trial production hydrate reservoir development is of great significance.

In this study, first, the fracture network's stimulating effect on long-term production behaviors in China's trial production area was explored. The influence of the well arrangement on development performance was clarified. Second, the influence of fracture distribution on development performance was resolved. Lastly, commercial CH₄ production after network fracturing was preliminarily estimated.

2. Numerical Model and Simulation Schemes

2.1. Geological Data

The studied reservoir is located in the Shenhu Area, at a water depth of 1266 m [8]. The reservoir parameters are shown in Table 1.

Table 1. The reservoir parameters of the trial production area. Reprinted with permission from Ref. [33]. Copyright 2024. Elsevier, Amsterdam, the Netherlands.

Interval	Depth (m bsf)	Thickness (m)	Effective Porosity (%)	Average Saturation (%)	Average Permeability (mD)
GHL	207.8~253.4	45.6	37.3	31	2.38
MXL	253.4~278	24.6	34.6	11.7 (S _H); 13.2 (S _G)	6.63
FGL	278~297	19	34.7	7.3	6.8

2.2. Model Establishment

Figure 1a shows a 3D model of W_H-D. The Y direction is the horizontal well drilling direction. It is generally assumed in numerical simulations that reservoir properties in the Y direction are homogeneous. Therefore, only 1 m needs to be simulated in this direction. This way, a 2D model can be used instead of a 3D model (Figure 1b). The 30 m thicknesses of overburden and underburden are set to ensure an accurate heat and pressure transmission calculation in the hydrate layer [2,34]. In the scheme of the wells arranged in the MXL (as shown in Figure 1b–e), the wells are designed in the upper part of the MXL to ensure the dissociation of hydrate in the GHL in long-term development. In the cases of the wells arranged in the GHL (as shown in Figure 1f–i), the wells are designed in the middle of the GHL, as this is beneficial to the hydrate in GHL dissociation. The fractures are equally distributed with a 4 m spacing (referred to the cluster spacing of reservoir reconstruction in China's trial engineering [9]) in cases with a fracture network. Figure 1j–m are the schematics of the cases with different fracture distributions, including fractures distributed both in the GHL and MXL together and only in the GHL.

2.3. Well and Fracture Design

The well and fracture generalizations have been explained in detail in previous studies [30,35]. In this study, the injection temperature and pressure of well_i were 60 °C and 20 MPa, respectively [36,37]. The production pressure of well_p was 4.5 MPa [38]. The generalization of the fracture network has been introduced in detail in our previous study [30]. The fracture conductivity was set as 10 D·cm.

2.4. Numerical Code

Tough + Hydrate (T+H) numerical code was used in this study. T+H is widely used in hydrate development simulations, and its accuracy has been verified [39–44]. The mathematical models used in this study were listed in reference [31].

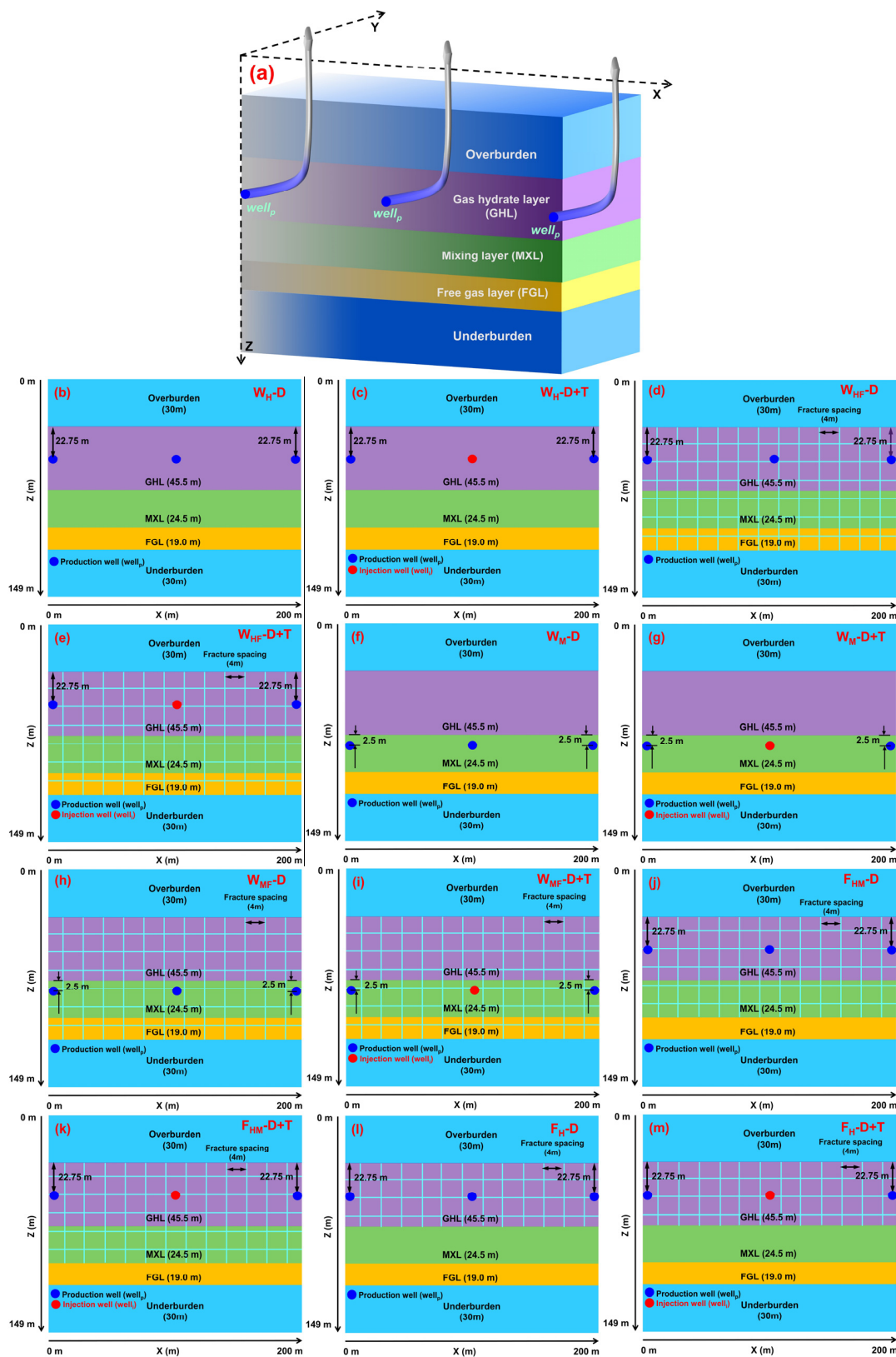


Figure 1. The schematics of the different cases in this study. (a): 3D model of W_H -D; (b): 2D model of W_H -D; (c): 2D model of W_H -D+T; (d): 2D model of W_{HF} -D; (e): 2D model of W_{HF} -D+T; (f): 2D model of W_M -D; (g): 2D model of W_M -D+T; (h): 2D model of W_{MF} -D; (i): 2D model of W_{MF} -D+T; (j): 2D model of F_{HM} -D; (k): 2D model of F_{HM} -D+T; (l): 2D model of F_H -D; (m): 2D model of F_H -D+T (the explanation of abbreviations see Section 2.6).

2.5. Initial and Boundary Conditions

The reservoir's vertical pressure distribution obeys hydrostatic pressure. Thus, the pressure at the interface between the GHL and the MXL is calculated to be 14.25 MPa. The temperature here is 15.90 °C, obtained from the phase diagram [39]. Logging data show the geothermal gradient in the studied area is 0.0437 m/°C [45]. By obtaining those data, the model's initial pressure and temperature can be calculated. Other parameters are listed in Table 2.

Table 2. Other parameters for model establishment.

Parameters	Value	Parameters	Value
Grain density ρ_R (all deposits)	2650 kg/m ³	Grain-specific heat	1000 Jkg ⁻¹ °C ⁻¹
Intrinsic permeability $k_x = k_y = k_z$ (overburden and underburden)	6.8×10^{-15} m ²	Relative permeability model	$k_{rA} = (S_A^*)^n$
			$k_{rG} = (S_A^*)^{n_G}$
			$S_A^* = (S_A - S_{irA}) / (1 - S_{irA})$
			$S_G^* = (S_G - S_{irG}) / (1 - S_{irG})$
Geothermal gradient	0.0437 m/°C	n	3.572
Capillary pressure model	$P_{cap} = -P_0 \left[(S^*)^{-1/\lambda} - 1 \right]^{1-\lambda}$	n_G	3.572
λ	0.45	S_{irA}	0.30
P_0	10 ⁵ Pa	S_{irG}	0.03
Fracture porosity Φ_F	0.38	Fracture spacing	4 m
Dry thermal conductivity $k_{\theta RD}$ (all deposits)	1.0 W/m/K	Wet thermal conductivity $k_{\theta RW}$ (all deposits)	3.1 W/m/K

2.6. Simulation Scenarios

The hydrate development methods investigated in this study include the depressurization method and depressurization combined with thermal water injection (hereafter referred to as the “combined method” for brevity). The wells' arranged layers including the MXL and GHL, as shown in Table 3, and the schematics of each scheme are shown in Figure 1.

Table 3. The simulation scenarios.

Development Methods		Well Location
W _M -D	depressurization	MXL
W _H -D		GHL
W _M -D+T	combined method	MXL
W _H -D+T		GHL
W _{MF} -D	depressurization stimulated by fracture network	MXL
W _{HF} -D		GHL
W _{MF} -D+T	combined method stimulated by fracture network	MXL
W _{HF} -D+T		GHL
development methods		Fracture distribution
F _{HMF} -D	depressurization	GHL, MXL, FGL
F _{HM} -D		GHL, MXL
F _H -D		GHL
F _{HMF} -D+T	combined method	GHL, MXL, FGL
F _{HM} -D+T		GHL, MXL
F _H -D+T		GHL

3. Results and Discussion

3.1. Fracture Network's Stimulation and the Influence of Well Arrangement on Development Performance

3.1.1. Spatial Evolution of Physical Parameters

Figures 2–4 show the S_H distributions of different development modes with different well arrangements at 360, 720, and 1095 days, respectively. For W_H -D, the hydrate decomposition performance was characterized by a slow hydrate decomposition front advancing speed and a piston-like hydrate decomposition mode (there are two hydrate decomposition modes, and their explanations have been explained in detail in previous studies [33,46]). At 1095 days, the hydrate decomposition range around well_p was only 20 m. In W_M -D, hydrate decomposition mainly occurred in the MXL. This was because the higher intrinsic permeability and lower S_H of the MXL make it have higher effective permeability, which was conducive to pressure drop spread. In addition, the hydrate decomposition in the MXL in W_M -D was no longer in piston-like mode (there existed about 25 m of partial-hydrate decomposition zone between the complete decomposition area and non-decomposition area). The better hydrate dissociation in the MXL of W_M -D made it have a better hydrate decomposition behavior than W_H -D. For W_H -D+T, the hydrate dissociation near well_p was the same as W_H -D. However, the hydrate dissociation front near well_i had expanded by nearly 40 m at 1095 days, which was significantly greater than that near the well_p. For W_M -D+T, due to the high effective permeability of the MXL, the hydrate decomposition area near the interface between the MXL and FGL surrounding well_i was significantly larger than that in W_H -D+T, which yielded a better hydrate decomposition performance than W_H -D+T. Compared with W_H -D, the hydrate decomposition of W_{HF} -D showed two remarkable characteristics. One was that the hydrate dissociation area in the hydrate layer near well_p was significantly larger (having reached 40 m at 1095 days). The other was that the hydrate in the MXL of W_{HF} -D had completely decomposed at 1095 days. These two characteristics determined that the improvement in reservoir permeability of the fracture network strengthened not only the pressure relief of GHL but also that of the MXL, thus significantly improving the hydrate decomposition. The hydrate in the MXL completely decomposed in W_{HF} -D, making its hydrate decomposition ability no longer inferior to W_{MF} -D. On the contrary, because well_p in W_{MF} -D was located in the MXL, it was not conducive to the pressure relief of GHL. As a result, the hydrate decomposition capacity of W_{HF} -D was higher than that of W_{MF} -D. Compared with W_H -D, W_H -D+T, W_{HF} -D, W_M -D, W_M -D+T, and W_{MF} -D, the hydrate decomposition ability of W_{HF} -D+T and W_{MF} -D+T showed great advantages. At 360 days, most of the hydrate in W_{HF} -D+T and W_{MF} -D+T had been decomposed. Comparing the S_H evolution in W_{HF} -D+T and W_{MF} -D+T, it is evident that the hydrate decomposition front in W_{HF} -D+T advanced toward well_p in a diamond shape, while in W_{MF} -D+T, due to the fast hydrate decomposition in the MXL, the contact area of the hydrate decomposition front with the injected water was significantly smaller than that of W_{HF} -D+T. Meanwhile, after the hydrate in the MXL decomposition was completed, the permeability difference between the hydrate layer and its underlying layers, including MXL and FGL, caused serious interlayer contradiction. This contradiction seriously reduced the hydrate decomposition rate, which was proven in the minimal change to the hydrate decomposition area in W_{MF} -D+T after 360 days. These two reasons led to the lower hydrate decomposition capacity of W_{MF} -D+T than W_{HF} -D+T.

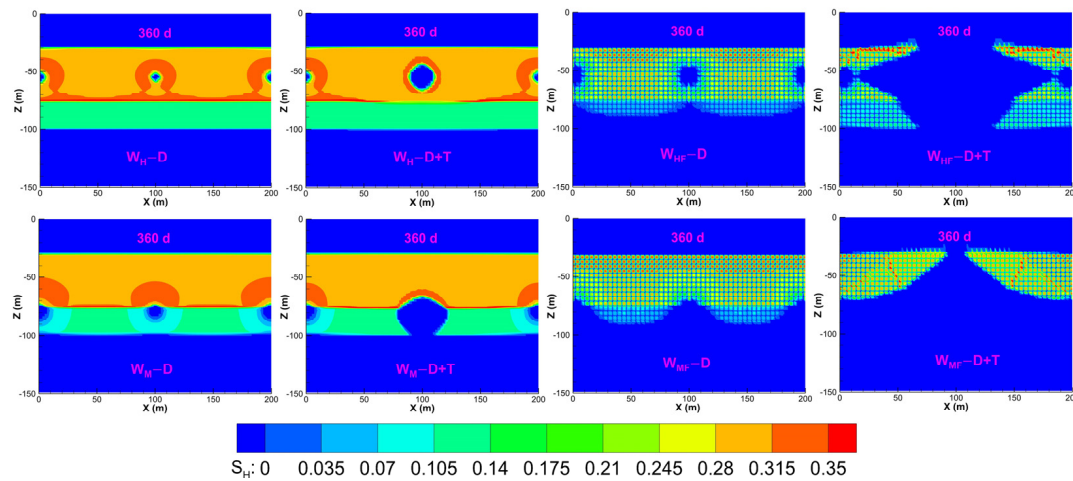


Figure 2. S_H distributions of different development modes with different well layout modes at 360 days.

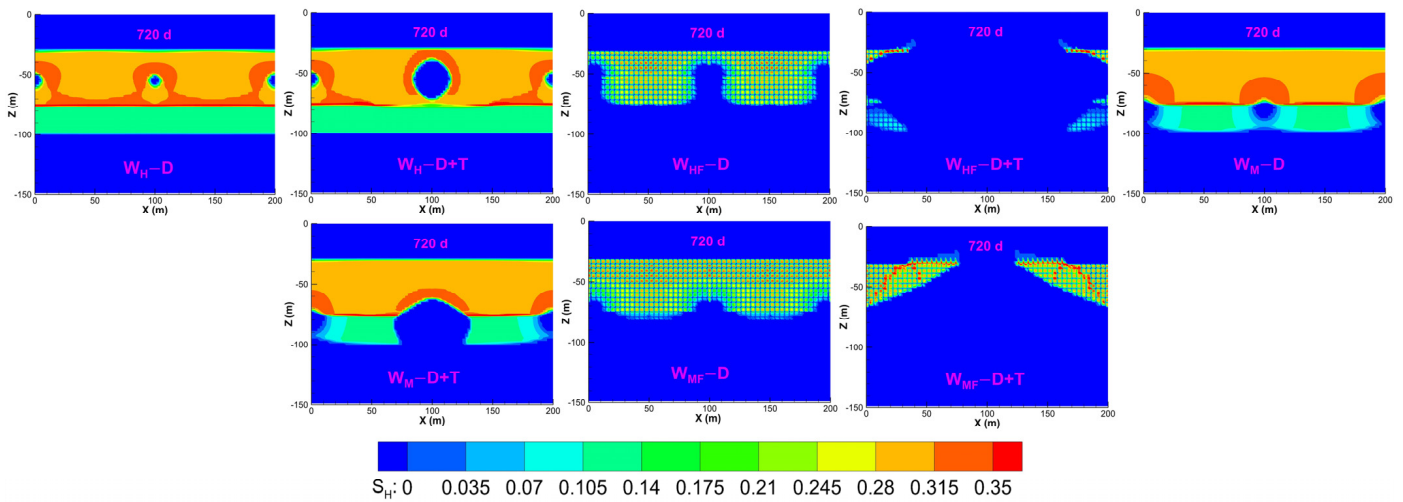


Figure 3. S_H distributions of different development modes with different well layout modes at 720 days.

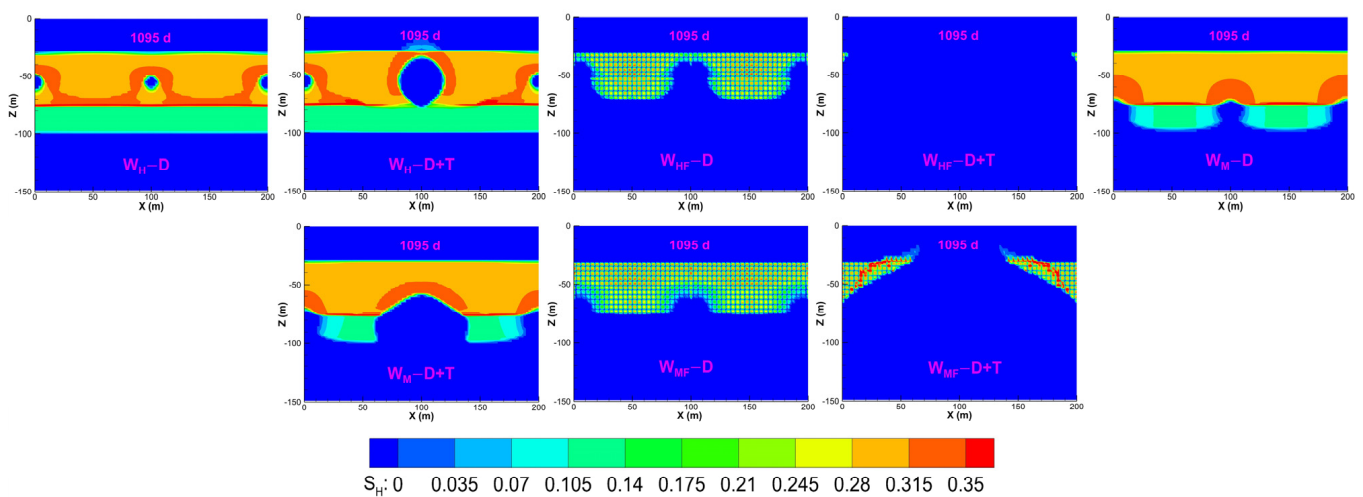


Figure 4. S_H distributions of different development modes with different well layout modes at 1095 days.

Figures 5–7 show the S_G distributions of different cases at 360, 720, and 1095 days, respectively. In W_H -D, the CH_4 saturations in the MXL and FGL hardly changed. However, in W_M -D, the S_G in the FGL below the wells decreased gradually. This indicated that

for the wells located in the GHL, the CH_4 in the FGL was difficult to recover. However, the wells located in the MXL had a better recovery for the CH_4 in the FGL. Compared with W_{H-D} , in the early development stage, as the fracture network enhanced the hydrate decomposition of the W_{HF-D} , the S_G of the W_{HF-D} in the GHL and MXL was significantly higher than that of the W_{H-D} . In the later development stage, the S_G of the W_{HF-D} in the MXL and FGL gradually decreased. This showed that after network fracturing, the wells arranged in the GHL achieved the recovery of CH_4 in the MXL and FGL. As the hydrate dissociation of the W_{HF-D} in the GHL was better than that of W_{MF-D} , the S_G and CH_4 distribution area of W_{HF-D} in the GHL was larger than that of W_{MF-D} . However, in the MXL and FGL, the S_G of W_{MF-D} decreased significantly faster than W_{HF-D} , showing that most CH_4 in the FGL and MXL of W_{MF-D} had been recovered at 1095 days. This showed that for depressurization production, after network fracturing, the wells arranged in the MXL had a better CH_4 recovery capacity in the MXL and FGL than did those arranged in the GHL. The most remarkable feature of the evolution of S_G in W_{H-D+T} and W_{M-D+T} was that the migration speed of CH_4 near well_i and well_p was slow. However, from the CH_4 distributions in W_{HF-D+T} and W_{MF-D+T} , it is evident that the fractures promoted the flow of CH_4 near well_i and well_p. At 360 days, a large volume of CH_4 near well_i in W_{HF-D+T} and W_{MF-D+T} has migrated into well_p.

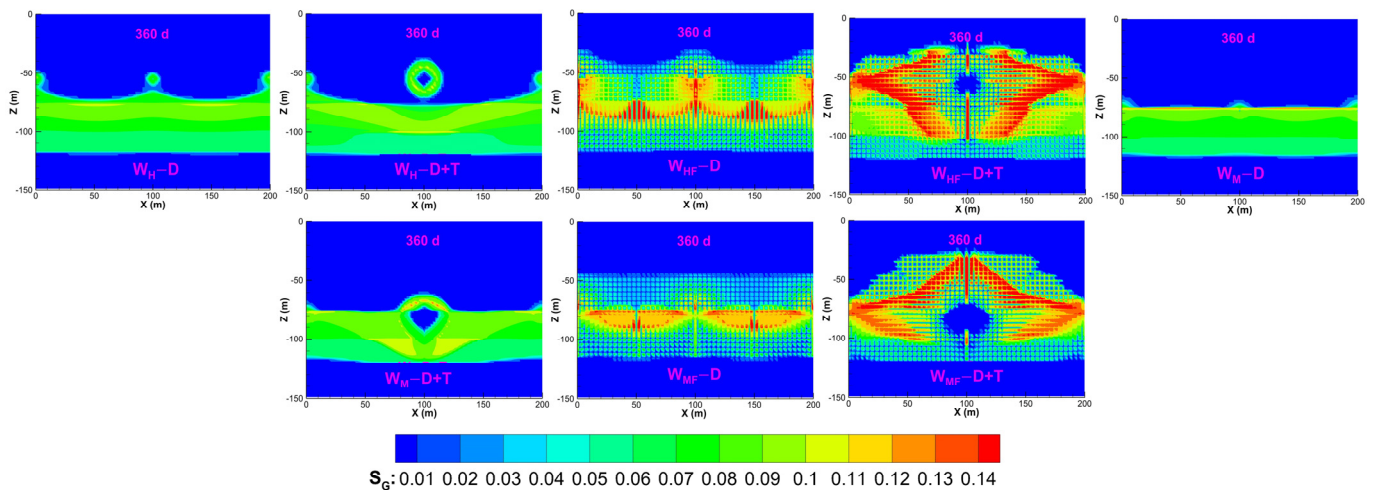


Figure 5. S_G distributions of different development modes with different well layout modes at 360 days.

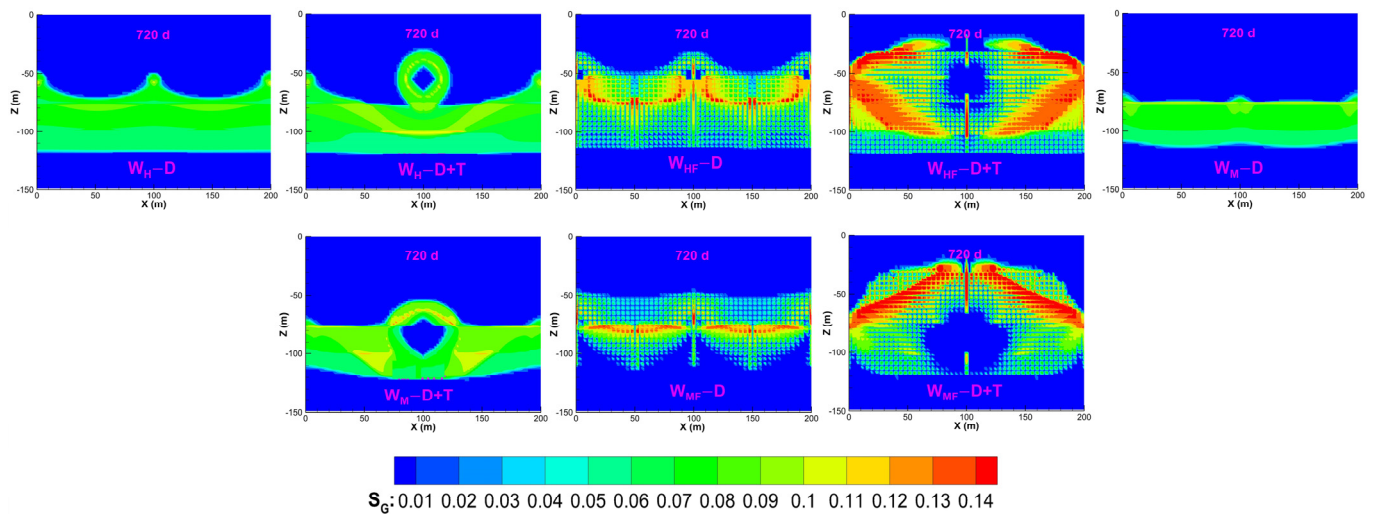


Figure 6. S_G distributions of different development modes with different well layout modes at 720 days.

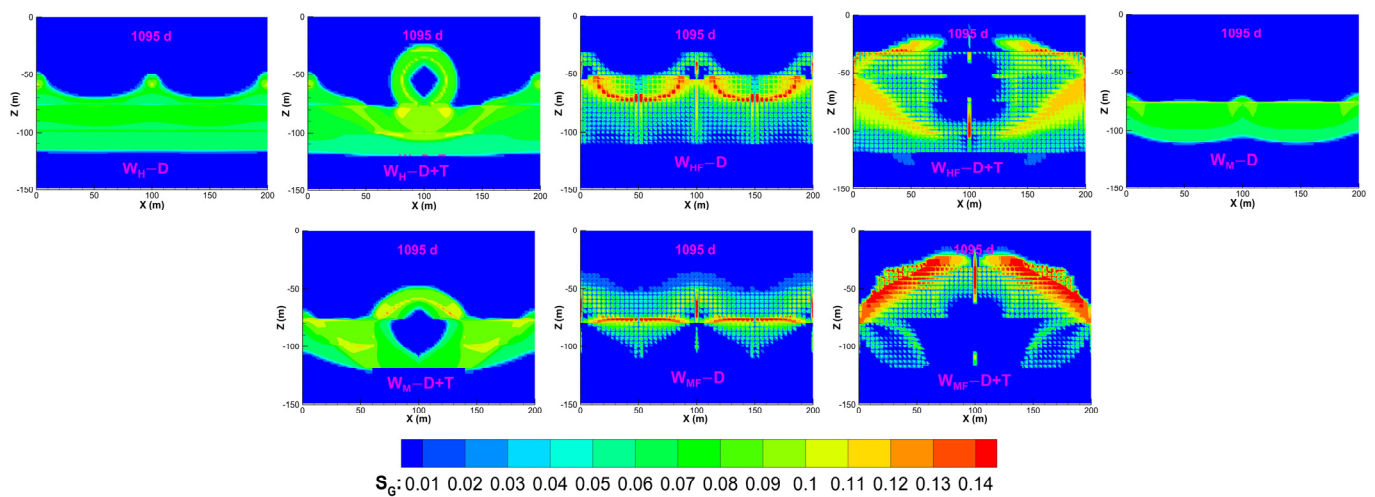


Figure 7. S_G distributions of different development modes with different well layout modes at 1095 days.

3.1.2. Hydrate Dissociation Performance

Figure 8 shows the evolutions of Q_R and R_d ($R_d = m_d/m_i$) when wells were located in GHL. For W_H-D , as shown in Figure 8b, the Q_R reached a stable value of about $5 \text{ m}^3/\text{d}$ over a short time. For W_H-D+T , the Q_R increased gradually during the whole development period. This was because the hydrate dissociation area near well_i increased, resulting in a gradual increase of the heating area near the injection well; as a result, the Q_R gradually increased. The Q_R in $W_{HF}-D$, as shown in Figure 8a, reached a high value (about $1000 \text{ m}^3/\text{d}$), then declined rapidly in a short time (about 50 days) and stabilized at about $100 \text{ m}^3/\text{d}$. The Q_R in $W_{HF}-D+T$ gradually decreased after the initial disturbance period; however, the decline rate after 360 days was significantly higher than that before 360 days. The rapid decrease in Q_R after 360 days can be explained by Figure 9. It is evident that after 360 days, the hydrate decomposition zone between well_p and well_i gradually connected. This increased the water-effective permeability between well_p and well_i and reduced the seepage resistance of injected water flowing to well_p. This greatly reduced the heating efficiency of the injection water to the hydrate reservoir, leading to the rapid reduction of Q_R . The evolution tendencies of Q_R in $W_M-D-W_{MF}-D+T$ were similar to that at $W_H-D-W_{HF}-D+T$, as shown in Figure 10.

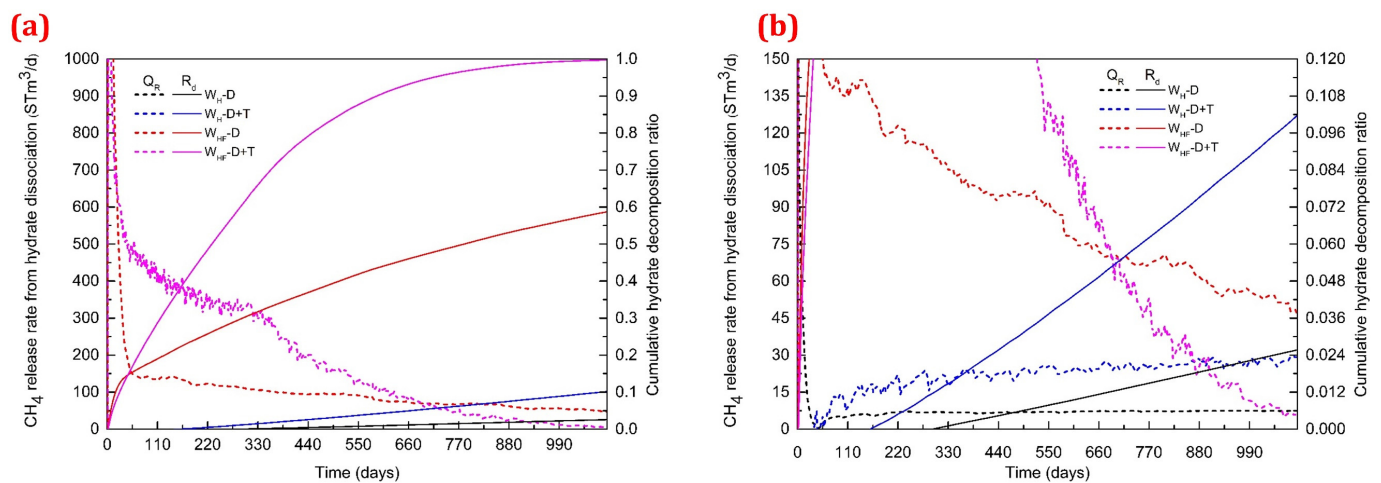


Figure 8. Evolutions of Q_R and R_d in different development methods when wells were located in the GHL ((a), left Y-axis range 0–1000; (b), left Y-axis range 0–150).

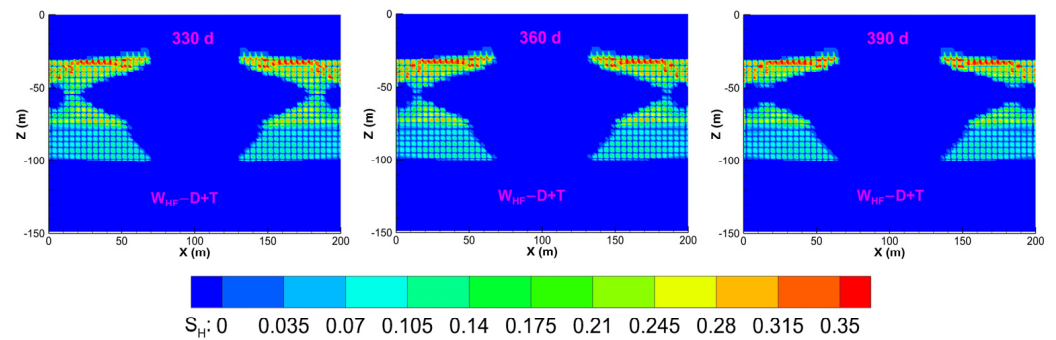


Figure 9. Hydrate saturation distributions of $W_{HF}-D+T$ at 330, 360, and 390 days.

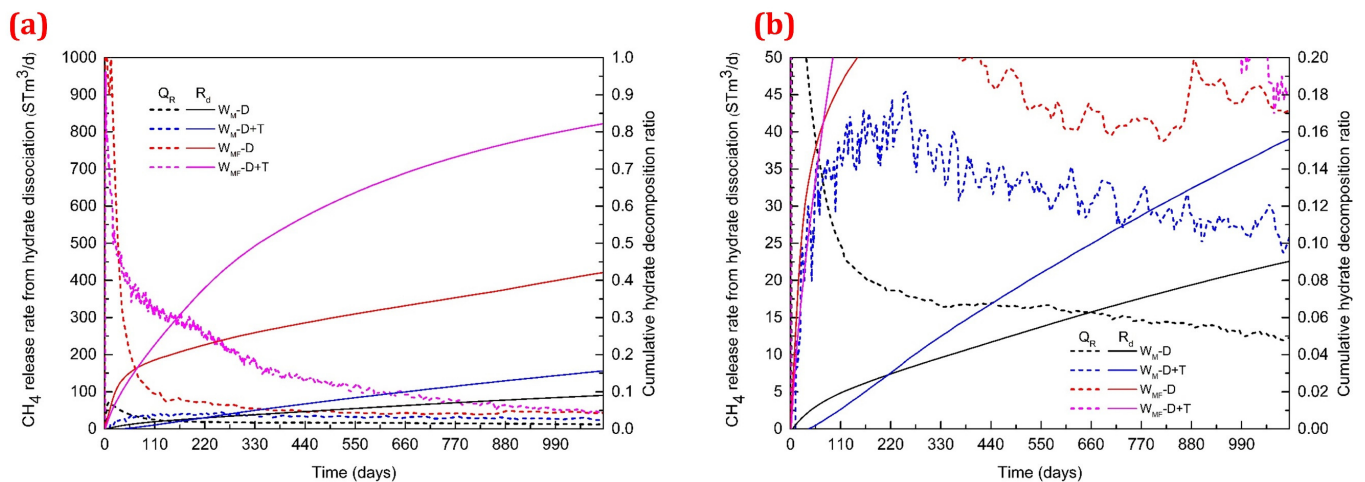


Figure 10. Evolutions of Q_R and R_d in different development methods when wells were located in the MXL ((a), Y-axis range 0–1000; (b), Y-axis range 0–50).

Figure 11 shows the Q_{ER} (V_R/t) in different cases. The Q_{ER} of $W_{MF}-D$ and $W_{MF}-D+T$ was about 5 times higher than that of W_M-D and W_M-D+T , and the Q_{ER} of $W_{HF}-D$ and $W_{HF}-D+T$ was over 15 times higher than that of W_H-D and W_H-D+T . This indicated that the fracture network had a great improvement in hydrate dissociation capacity with both depressurization and the combined method. In addition, the average Q_R at W_M-D and W_M-D+T was 3.5 and 1.5 times higher than those at W_H-D and W_H-D+T , respectively. However, the average Q_R at $W_{HF}-D$ and $W_{HF}-D+T$ was 1.4 and 2.3 times higher than those at $W_{MF}-D$ and $W_{MF}-D+T$, respectively. This indicated that without a fracture network, the wells arranged in the MXL had a better hydrate dissociation capacity than those in the GHL. However, with the fracture network, the result was reversed.

3.1.3. CH₄ Production Performance

Figure 12 shows the evolutions of Q_P and V_P when wells are located in the GHL. The evolutions of Q_P at W_H-D and W_H-D+T were consistent. Q_P reached its peak value in a short time and then tended to be stable. After the CH₄ in the MXL migrated into the production well at 360 days, the Q_P gradually increased and then tended to be stable. In addition, as the CH₄ near well_i in W_H-D+T could not migrate into well_p (as shown in Figures 5–7), the Q_P at W_H-D+T was lower than that at W_H-D . The evolution of Q_P at $W_{HF}-D$ was significantly different from at W_H-D . The Q_P at $W_{HF}-D$ quickly reached its peak value of about 162 m³/d and, after that, gradually declined. Due to the contribution of CH₄ in the MXL to CH₄ production, Q_P was stable at about 125 m³/d at 220 days. After 550 days, as the CH₄ saturation in the MXL gradually decreased, the Q_P gradually decreased accordingly; this can be found in Figure 13. The Q_P at $W_{HF}-D+T$ began to rise sharply at 180 days; this was because the CH₄ released from hydrate thermal decomposition

flowed to well_p through the fracture network. As the advance of the highly saturated CH₄ front migrated to well_p, the Q_P continued to rise. After the highly saturated CH₄ front reached well_p (at about 550 days, as shown in Figure 14), the Q_P gradually decreased.

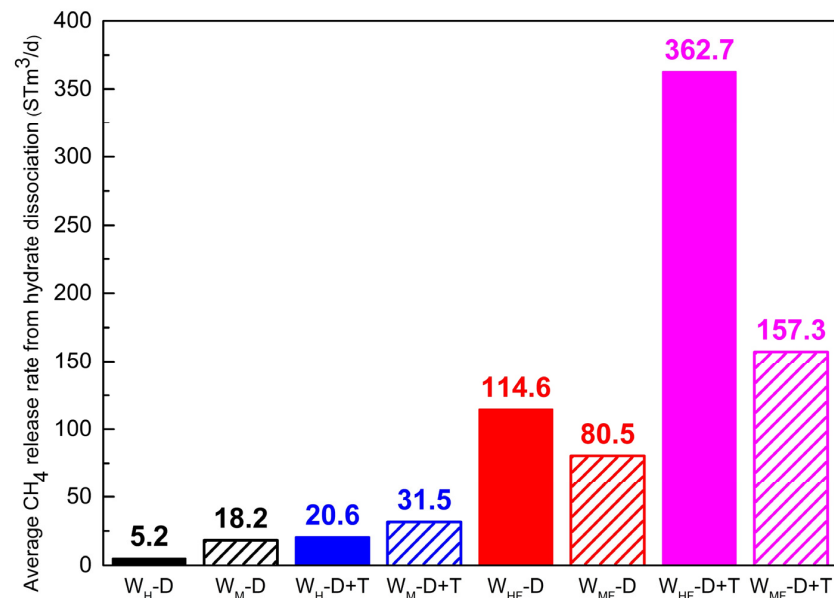


Figure 11. The Q_{ER} in different cases.

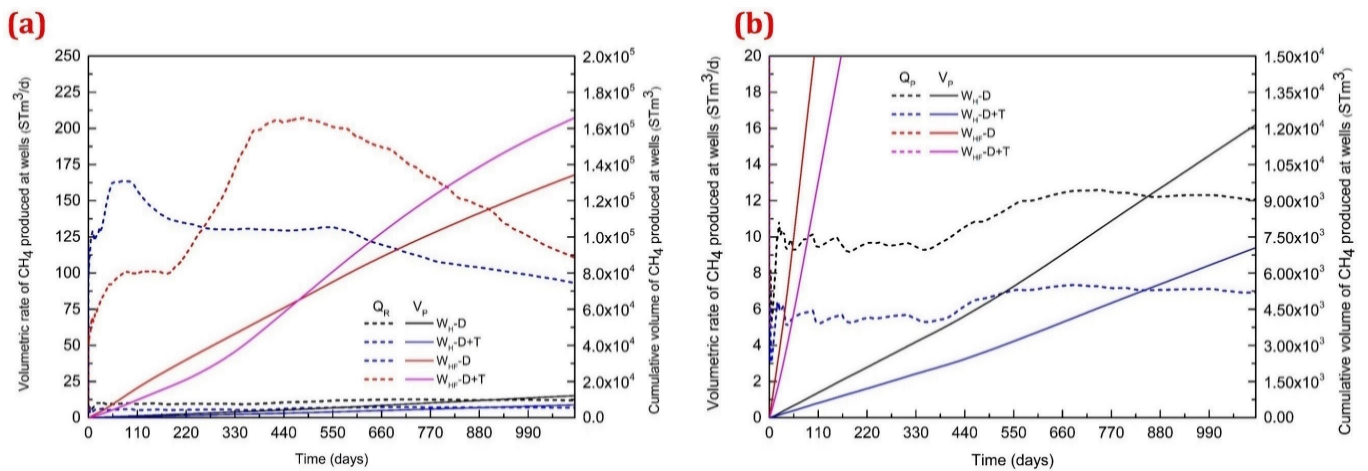


Figure 12. Evolutions of Q_P and V_P with different development methods when wells were located in the GHL ((a), Y-axis range 0–250; (b), Y-axis range 0–20).

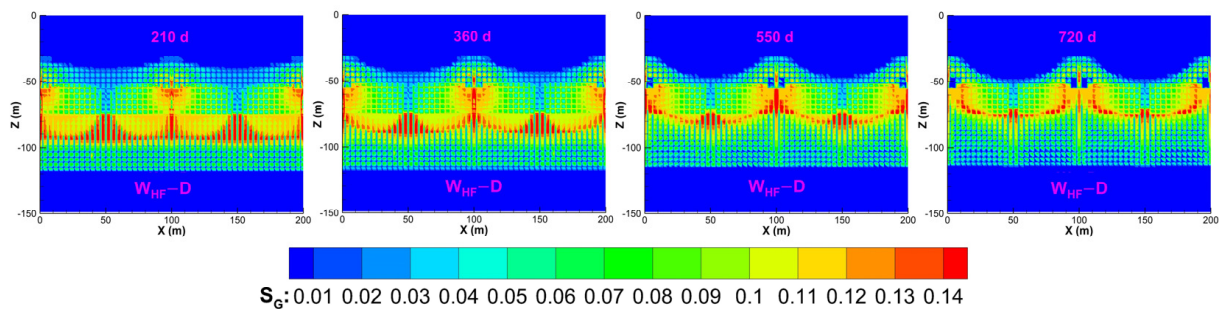


Figure 13. Evolution of S_G of W_{HF}-D over 210–720 days.

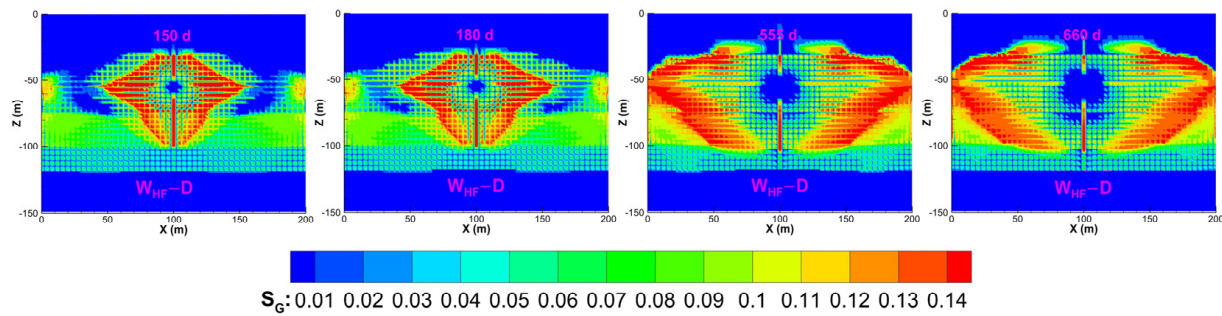


Figure 14. Evolution of S_G of W_{HF-D+T} over 150–660 days.

The Q_P in W_{M-D} , W_{M-D+T} , and W_{MF-D} reached a large value at the initial development moment and then decreased gradually, as shown in Figure 15. This was because the pressure disturbance near well_p at the initial development moment was very large and the MXL had sufficient free CH_4 , which resulted in a large instantaneous Q_P . The evolution tendency of Q_P in W_{MF-D+T} was identical to that in W_{HF-D+T} .

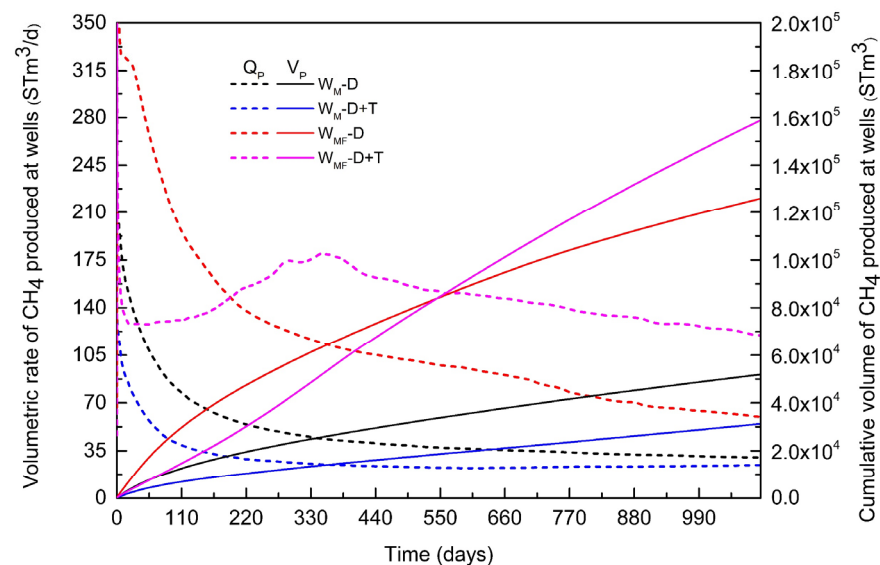


Figure 15. Evolutions of Q_P and V_P with different development methods when wells were located in the MXL.

The Q_{EP} (V_P/t) in different cases is shown in Figure 16. The Q_{EP} of W_{MF-D} and W_{MF-D+T} was about 2.4 and 5.1 times higher than those of W_{M-D} and W_{M-D+T} , respectively. The Q_{EP} of W_{HF-D} and W_{HF-D+T} was 11.0 and 23.7 times higher than those of W_H-D and W_H-D+T , respectively. This proved that the fractures showed a great improvement on CH_4 production capacity with both depressurization and the combined method. In addition, the Q_{EP} of W_{M-D} and W_{M-D+T} was 4.3 times higher than those of W_H-D and W_H-D+T , respectively. This indicated that without a fracture network, the wells arranged in the MXL had significantly better CH_4 production than those in the GHL. However, the Q_{EP} of W_{HF-D} was 6.3% higher than that of W_{MF-D} , and the V_P of W_{HF-D+T} was 4.4% higher than that of W_{MF-D+T} . This indicated that with a fracture network, the wells arranged in the GHL had a better CH_4 production than those arranged in the MXL; however, their difference was minimal, considering that the Q_{ER} of W_{HF-D+T} was 2.3 times higher than that of W_{MF-D+T} . This indicated that the three-spot well pattern may not be enough to fully recover the CH_4 in the reservoir. It is crucial to optimize the injection–production well pattern to improve the CH_4 production capacity of W_{HF-D+T} .

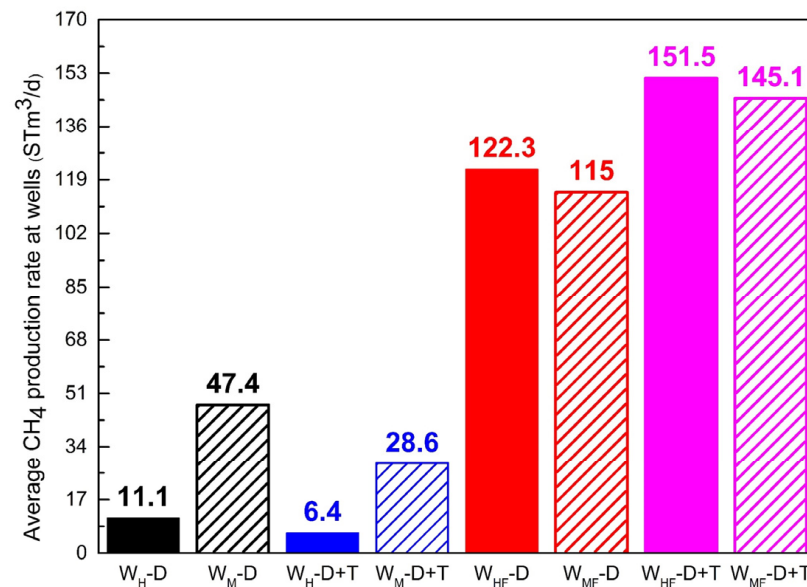


Figure 16. Q_{EP} in different cases.

3.1.4. Water Production Performance

The R_{GW} (V_w/V_P) of W_M-D and that of W_M-D+T were 16.5 and 17.2, respectively; that of W_H-D and that of W_H-D+T were 9.4 and 4.9, as shown in Figure 17. The R_{GW} of W_{MF}-D and that of W_{MF}-D+T were 4.1 and 5.0, respectively; those values of W_{HF}-D and W_{HF}-D+T were 5.1 and 6.8. This indicated that without a fracture network, the wells arranged in the MXL had a significantly larger R_{GW} than those arranged in the GHL; however, with a fracture network, the result was reversed.

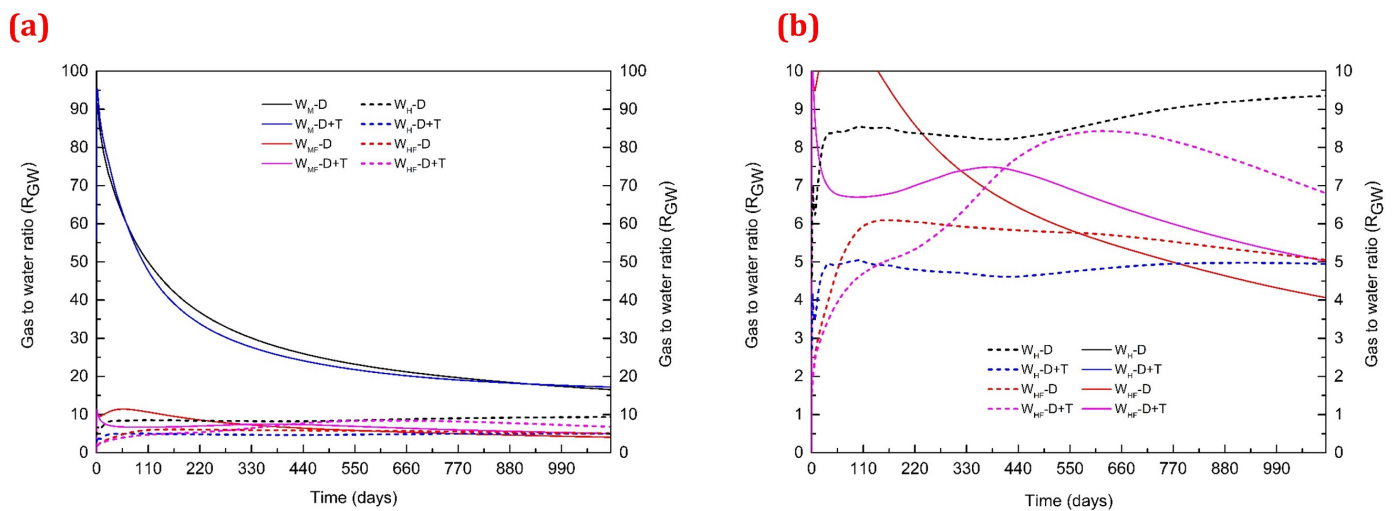


Figure 17. Evolutions of R_{GW} in different development methods ((a), Y-axis range 0–100; (b). Y-axis range 0–10).

3.2. The Influence of Fracture Distribution

The results in Section 3.1 show that after network fracturing, better production behavior can be obtained by arranging production wells in the GHL. Therefore, in this section, we explored the effect of different fracture distributions on hydrate development performance with this well layout mode; the corresponding model schematics are shown in Figure 1.

3.2.1. Hydrate Dissociation Behavior

As shown in Figure 18, the Q_R at F_H -D was higher than that at F_{MH} -D before 600 days. The reason for this can be explained by the R_P and S_H distributions, as shown in Figure 19. The diffusion of low pressure from well_p in the GHL of F_H -D was stronger than that from F_{MH} -D. This stronger low-pressure diffusion made the hydrate decomposition rate in the GHL in F_H -D greater than that in F_{MH} -D, resulting in a higher Q_R of F_H -D than that of F_{MH} -D. Over days 160–330, the Q_R at F_{MHF} -D was higher than that at F_H -D; after that, the result was reversed. From the T_R and S_H distributions of the F_{MHF} -D and F_H -D in Figure 19, it found that in F_{MHF} -D, as the fracture network connected with the FGL, formation water with a high temperature in the FGL penetrated the MXL. This greatly promoted hydrate decomposition in the MXL at F_{MHF} -D. However, the diffusion of low pressure in the GHL of F_{MHF} -D was the worst, which led to the worst hydrate decomposition capacity in the GHL. Therefore, as the hydrate below well_p in the MXL of F_{MHF} -D gradually dissociated, the Q_R of F_{MHF} -D gradually became smaller than that of F_H -D. The final R_d values at F_{MHF} -D – F_H -D were 58.7%, 58.3%, and 60.1% respectively. This showed that the F_H -D has the best hydrate decomposition capacity; however, the differences between them were minimal. This indicated that the fracture distribution had a minimal effect on the hydrate decomposition behavior.

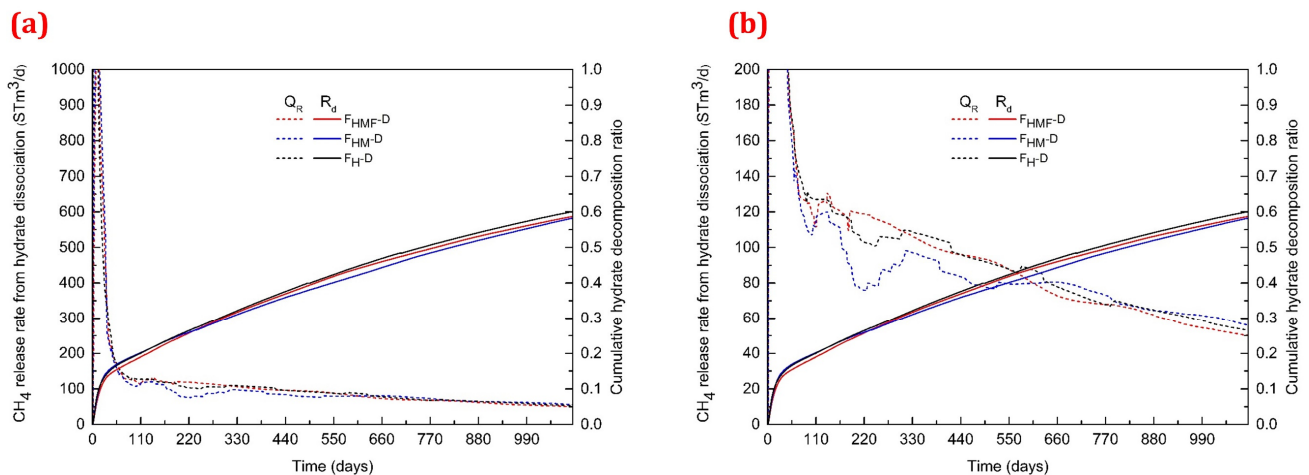


Figure 18. Evolutions of Q_R and R_d with different fracture distributions of the depressurization method ((a), left Y-axis range 0–1000; (b), left Y-axis range 0–200).

As shown in Figure 20, the Q_R values at F_{MHF} -D+T and F_{MH} -D+T were nearly identical and better than those at F_H -D+T. This can be illustrated by Figure 21, which shows the S_H of F_{MHF} -D+T, F_{MH} -D+T, and F_H -D+T at 450 days. We found that the fractures in the MXL in F_{MHF} -D+T and F_{MH} -D+T promoted hydrate decomposition in the MXL, while only a little hydrate decomposition was promoted in the MXL of F_H -D+T. This indicated that the conductive function of fractures was the main controlling factor of hydrate thermal decomposition. This resulted in a better hydrate dissociation behavior of F_{MHF} -D+T and F_{MH} -D+T than F_H -D+T.

3.2.2. CH_4 Production Behavior

The Q_P at F_H -D– F_{MHF} -D increased in turn before 160 days, as shown in Figure 22. This was because the fractures of F_{MH} -D connected to the MXL, while the fractures of F_{MHF} -D connected the MXL and the FGL. Those two layers made a favorable contribution to CH_4 production in the early development period. With the advance of development, the differences in Q_P between them decreased gradually. The final V_P values at F_H -D– F_{MHF} -D were $1.34 \times 10^5 m^3$, $1.38 \times 10^5 m^3$, $1.35 \times 10^5 m^3$, respectively; the differences between them were extremely small. This indicated that for the depressurization method, the fracture distribution had a minimal effect on the CH_4 production. The Q_P values at F_{MH} -D+T

and $F_{MHF-D+T}$ were nearly identical during the whole development period, as shown in Figure 23. However, due to lacking the contributions of the MXL and FGL to CH_4 production, the Q_P at F_H-D+T was smaller than those at $F_{MH}-D+T$ and $F_{MHF-D+T}$ after 440 days. The final V_P values at $F_H-D+T - F_{MHF-D+T}$ were $1.51 \times 10^5 m^3$, $1.67 \times 10^5 m^3$, $1.66 \times 10^5 m^3$, respectively. The final V_P values at $F_{MH}-D+T$ and $F_{MHF-D+T}$ were 10.1% higher than that at F_H-D+T . This indicated that for the CH_4 production of the combined method, the arrangement of fractures both in hydrate and MXL had a better CH_4 production capacity; however, the arrangement of fractures in the FGL was useless.

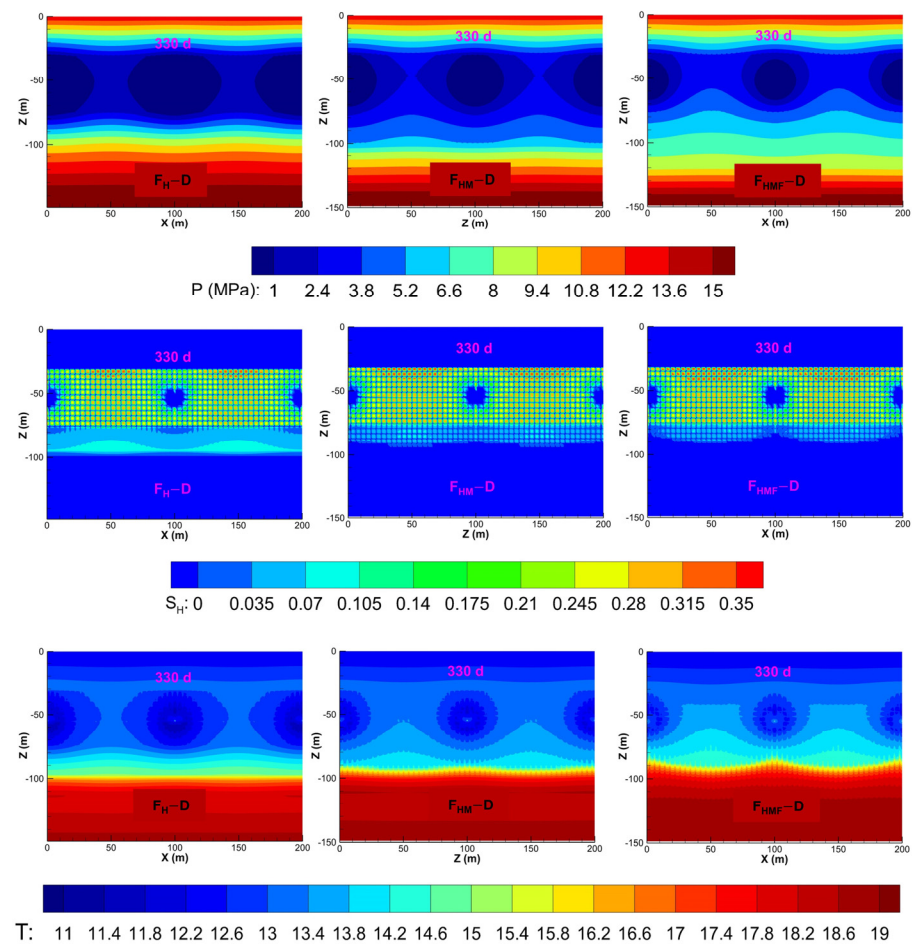


Figure 19. Distributions of P_R , S_H , and T_R at 330 days of $F_{MHF-D} - F_H-D$.

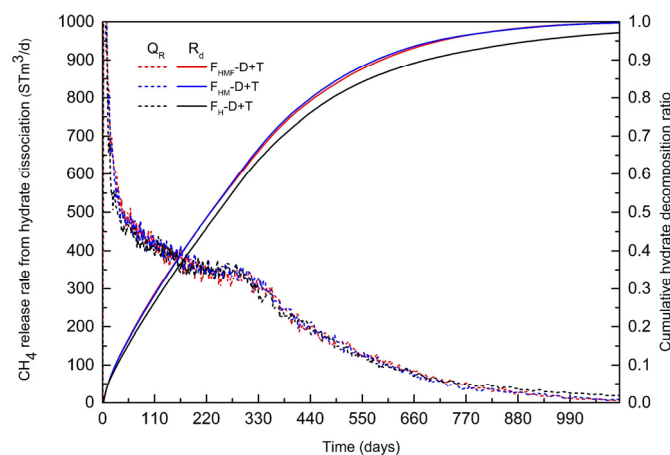


Figure 20. Evolutions of Q_R and R_d in different fracture distributions of the combined method.

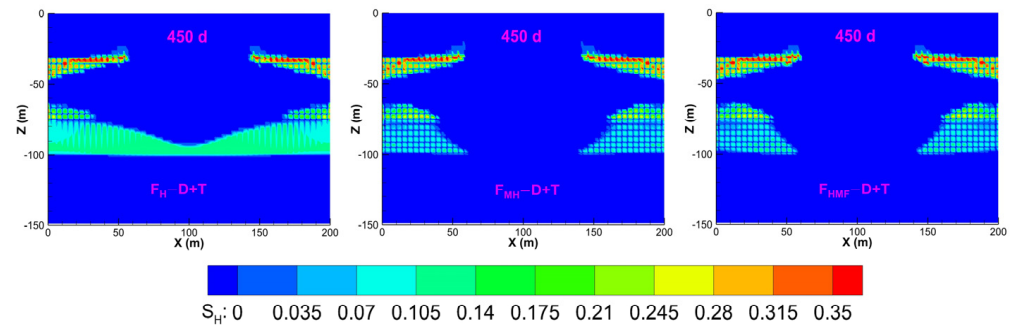


Figure 21. S_H of $F_{MHF}-D+T - F_H-D+T$ at 450 days.

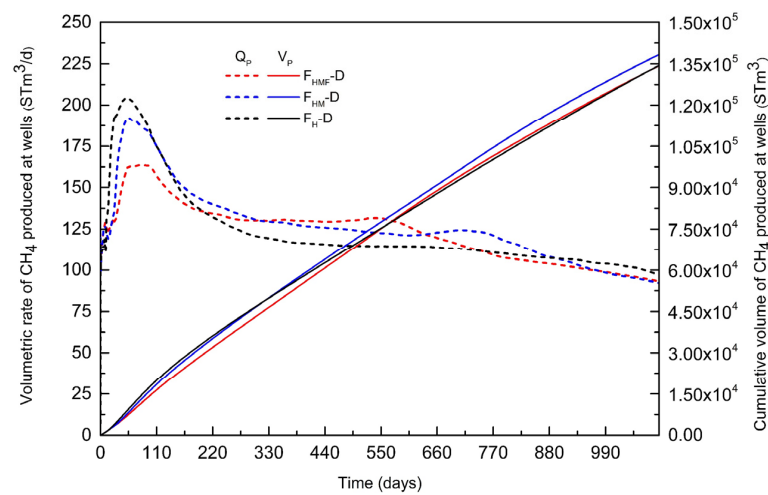


Figure 22. Evolutions of Q_p and V_p at $F_{MHF}-D - F_H-D$.

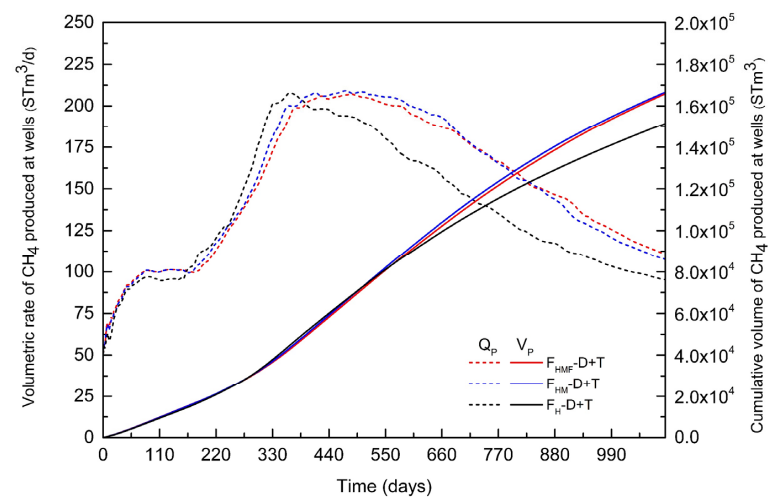


Figure 23. Evolutions of Q_p and V_p at $F_{MHF}-D+T - F_H-D+T$.

3.2.3. Water Production Behavior and Summary of the Influence of Fracture Distribution on Stimulation Behavior

As shown in Figures 24 and 25, the final R_{GW} values at $F_{MHF}-D - F_H-D$ were 6.16, 5.71, and 4.82, respectively. This indicated that the fractures in MXL and FGL enhanced water production and decreased R_{GW} . Therefore, for the depressurization method, fracturing in the GHL had the best production behavior. The final R_{GW} values at $F_{MHF}-D+T - F_H-D+T$ were 6.15, 6.75, and 6.80, respectively, indicating that the fracture distribution has a minimal effect on the water production of the combined method. Considering hydrate

decomposition, the CH_4 production and water production of $F_{\text{MHF-D+T}}$ and $F_{\text{MH-D+T}}$ were similar and were better than that of $F_{\text{H-D+T}}$; it was determined that for the combined method, fracturing both in the hydrate and MXL had an optimal production behavior, while fracturing in FGL was unnecessary.

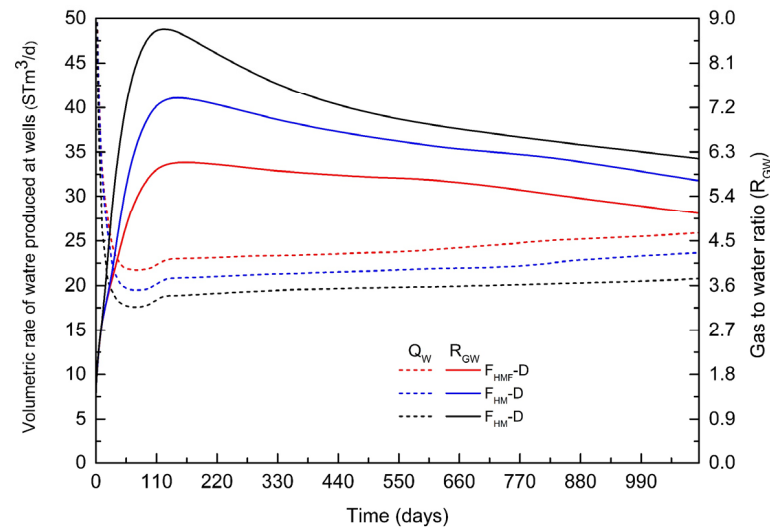


Figure 24. Evolutions of Q_W and R_{GW} at $F_{\text{MHF-D}} - F_{\text{H-D}}$.

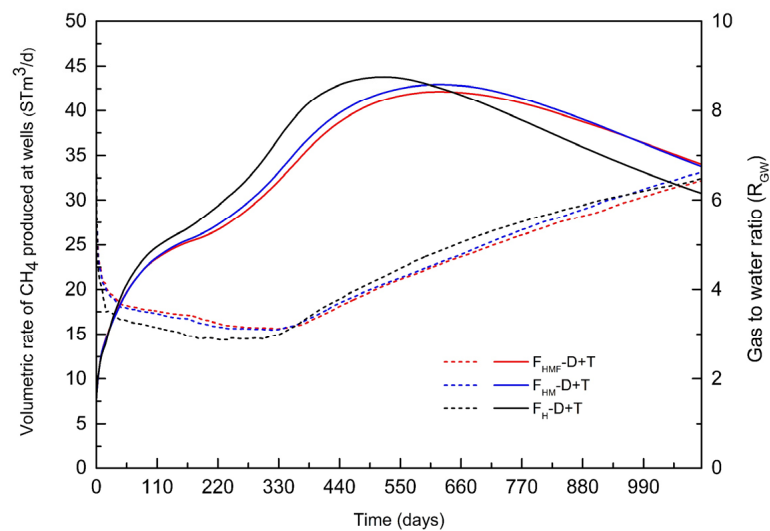


Figure 25. Evolutions of Q_W and R_{GW} at $F_{\text{MHF-D+T}} - F_{\text{H-D+T}}$.

3.3. Commercial Production Evaluation of Shenhu Trial Production Area after Network Fracturing

Currently, it is crucial to evaluate whether commercial CH_4 production can be realized, as it plays an important supporting and guiding role in the follow-up research of hydrate development.

Here, we introduce three indexes. (1) The CH_4 production rate in a unit horizontal well section length, Q_{up} ($Q_{up} = V_P/N_W/L_W$): As well_p on both sides of the model has only half the productivity, as shown in Figure 1, the N_W values from the depressurization method and combined method are 2 and 1, respectively. The L_W is 1 m in our models. (2) The horizontal well lengths required to achieve a CH_4 production rate of $6 \times 10^4 \text{ m}^3/\text{d}$ ($L_{CW} = 6 \times 10^4 \text{ m}^3/\text{d}^{-1}/Q_{up}$): $6 \times 10^4 \text{ m}^3/\text{d}$ is proposed by Japan [47]. (3) The maximum possible horizontal well drilling length in Shenhu Reservoir, L_O : this value is 1228 m as estimated by Li et al. [48].

Figure 26 shows Q_{up} and L_{CW} in different cases. Ma et al. [16] and Yu et al. [29] numerically investigated the stimulation potential of single horizontal fracture and single horizontal fracture combined with multi-branch fractures, respectively, using the depressurization method in the China trial production area. The maximum Q_{up} and minimum L_{CW} in their studies are also shown in Figure 26. It was found that the Q_{up} in cases without hydraulic fractures and with simple hydraulic fractures were very low, resulting in a correspondingly large L_{CW} . However, the cases with a fracture network showed a greatly superior Q_{up} . Their L_{WC} values are less than 1228 m, especially in the combined method are less than 500 m. This shows that both the depressurization method and combined method have the potential to reach a commercial CH_4 production rate after network fracturing in China's trial production area.

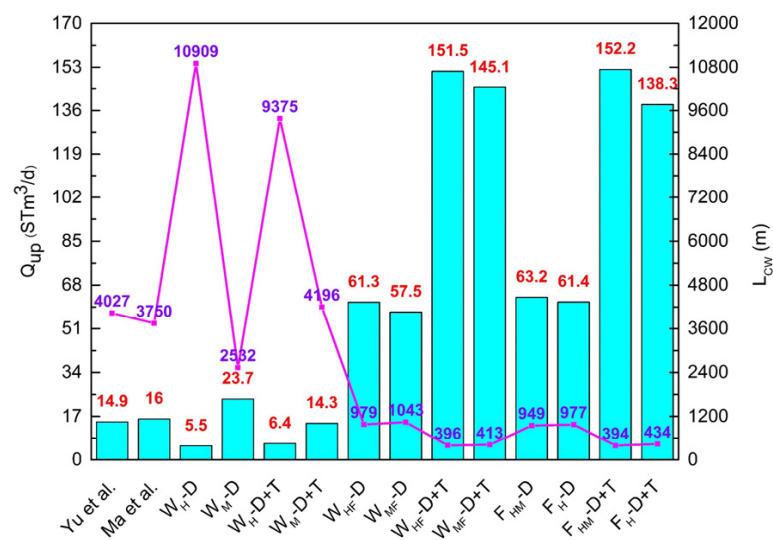


Figure 26. The Q_{up} and L_W in different cases [16,29].

4. Conclusions

In this study, the fracture network's stimulation on the second trial production area of China considering the presence of multiple layers was investigated. First, the fracture network's stimulation and the influence of well arrangement on hydrate development performance were explored. Second, the effect of fracture distribution on development was revealed, including fracture distribution in the hydrate layer (GHL), in GHL and mixed layer (MXL), and in GHL, MXL, and free gas layer (FGL). Last, the commercial CH_4 production potential of the trial production reservoir after fracture network fracturing was preliminarily evaluated. The main conclusions were as follows:

1. A fracture network has the stimulation potential to make the trial production reservoir reach commercial CH_4 production rates. With the fracture network, the CH_4 production rate in unit horizontal well length of depressurization and combined methods were 61.3 and 151.5 m^3/d , and the corresponding horizontal well lengths required were estimated to be 979 and 396 m, while the Q_{up} of those without fracture network were only 23.7 and 14.3 m^3/d .
2. Without a fracture network, the wells arranged in the MXL have a significantly better hydrate development than those arranged in the GHL. However, with the fracture network, the wells arranged in the MXL were not conducive to reservoir pressure relief, which had an adverse effect on hydrate decomposition. Thus, the wells arranged in the GHL had a better development behavior than those arranged in the MXL.
3. For depressurization, the fractures distributed in the MXL and FGL inhibited reservoir pressure relief and enhanced water production. Therefore, the best production behavior can be obtained by fracturing in the GHL. In the combined method, the fracture conductive function was the main controlling factor of hydrate thermal decomposition.

The best production behavior can be obtained by fracturing in the GHL and the MXL, while in the FGL, this was unnecessary.

In this study, the homogeneous model was used, and we were not concerned with energy efficiency. In future studies, a refined reservoir model should be established. Reservoir characteristics and free gas distribution need to be fully considered. Productivity estimations and fracture stimulation law with multiple factors need to be further clarified. Energy efficiency should be optimized considering multiple factors.

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Conflicts of Interest: The authors declare no conflict of interest.

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