

Original Paper

Optimizing depressurization timing for enhancing the efficiency of geothermal-assisted co-production of gas hydrate and deep gas

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ABSTRACT

The synergistic production of gas hydrates and deep gas reservoirs assisted by the geothermal energy transport via circulating water is significantly influenced by the temporal coordination of reservoir production schedules. However, the correlation between production timing and system performance remains unexplored. This work has for the first time systematically demonstrated the decisive role of choosing the production timing in determining the production efficiency. Four combined extraction methods for the co-operation of hydrate reservoirs and deep gas reservoirs have been designed. Experimental results demonstrate that deep gas reservoirs maintain high productivity independent of hydrate decomposition dynamics. This finding highlights the critical role of deep gas production timing in modulating geothermal energy transport to accelerate hydrate dissociation. Strategic delay of deep gas production until after initial hydrate reservoir depressurization was found to elevate circulating water temperatures, thereby expanding the heat distribution within the hydrate reservoir. This approach increased hydrate production efficiency by 6.79% compared to simultaneous production of both reservoirs. To maximize this thermal enhancement effect, deep gas production was further delayed to the early and middle stages of the hydrate reservoir's constant-pressure phase. Results revealed that sustained high-temperature water circulation until the mid-constant-pressure stage could boost cumulative geothermal energy release, achieving a 10.49% further improvement in hydrate production efficiency. These findings establish a positive correlation between deep gas production timing and hydrate recovery performance. The study provides actionable insights for optimizing field-scale co-production strategies, where deliberate sequencing of reservoir production can significantly enhance geothermal-driven hydrate dissociation rates.

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1. Introduction

Commercial production of natural gas hydrate (NGH) presents a viable solution for enhancing national energy security while

supporting environmental objectives related to carbon peak and carbon neutrality (Cozzi et al., 2025; Ma et al., 2024; Zhang et al., 2025b). However, field trials conducted worldwide have revealed critical challenges, including low gas production rates and limited

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sustained production capacity, which hinder large-scale NGH production (Anderson et al., 2011; Sohn et al., 2024; Yamamoto et al., 2014, 2019). When employing the depressurization method for hydrate production, the initial rapid pressure decline in the reservoir provides a strong driving force for hydrate dissociation (Chen et al., 2020; Ji et al., 2026; Zhang et al., 2025a). However, as production transitions into the prolonged constant-pressure stage, the slow heat transfer from surrounding formations leads to a significant reduction in dissociation efficiency (Chen et al., 2023; Gong et al., 2025; Kim et al., 1987). To address this limitation, geothermal energy, a clean, naturally abundant, and globally distributed resource, has been explored as an effective heat source to enhance dissociation kinetics (Feng et al., 2024; Hussain et al., 2017; Song et al., 2018). Current geothermal-assisted hydrate production strategies can be categorized into two approaches: Artificial injection: artificially injecting working fluids (e.g., CO₂ or water) into the geothermal layer, and then the high-temperature working fluids are injected into the hydrate

layer (see Fig. 1(a) and (b)) (Liu et al., 2018, 2019; Qin et al., 2025). Natural drive: The inherent pressure differential between hydrothermal/gas-rich layers and the hydrate reservoir facilitates the influx of hot fluids (see Fig. 1(c) and (d)) (Cheng et al., 2023; Liu et al., 2020; Yang et al., 2023). Studies indicate that CO₂ injection not only enhances natural gas production by 305% but also enables CO₂ sequestration ($2.11 \times 10^7 \text{ m}^3$) (Li et al., 2024; Liu et al., 2018; Wei et al., 2022). Alternatively, water injection promotes dissociation of ~25% of reservoir hydrates, yielding $1.60 \times 10^7 \text{ m}^3$ of natural gas (Chen et al., 2022; Hu et al., 2024). For natural drive systems, geothermal gases (shallow/deep-sourced) have been shown to improve production efficiency, mitigate thermal depletion, and enhance heat exchange between the hydrate layer and surrounding formations (Li et al., 2026; Zhao et al., 2022b, 2025a). Despite these advances, existing geothermal-assisted methods exhibit critical limitations: CO₂-based systems increase post-processing costs due to elevated CO₂ content in produced gas (Cai et al., 2025; Niu et al., 2023; Wang et al., 2025). Water-

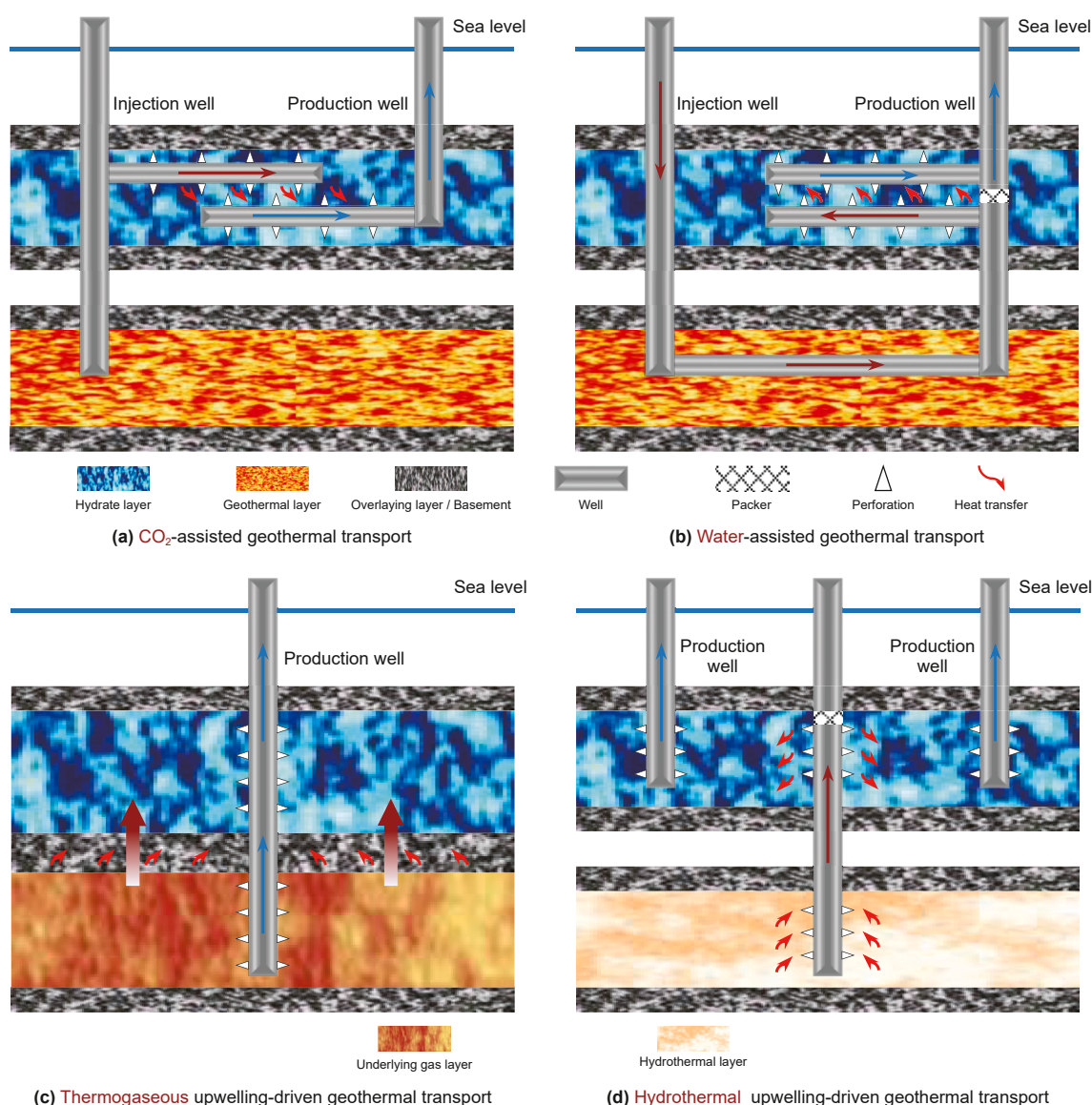


Fig. 1. Diagram of geothermal energy injection methods (the images were adapted from Ref. (Liu et al., 2020; Liu et al., 2018; Liu et al., 2019; Zhao et al., 2025a)).

dominated systems impede mass transfer by forming liquid films around hydrate particles (He et al., 2022; Jiang et al., 2025; Kou et al., 2023). Gas-driven systems suffer from low thermal efficiency due to the poor heat capacity of rising gases (Fan et al., 2025; Jin et al., 2024; Qiu et al., 2026). To overcome these constraints, this study proposes an innovative geothermal development concept: a circulating water pipeline linking the production platform, hydrate layer, and deep gas reservoir. This system leverages heat absorption-release cycles to efficiently extract and deliver geothermal energy. Coupled with hydrate-deep gas co-production, this approach aims to synergistically enhance gas recovery while reinforcing hydrate dissociation dynamics, offering a sustainable pathway for commercial NGH production (Li et al., 2023; Wang et al., 2025; Ye et al., 2025b).

Our prior research has demonstrated that geothermal transport characteristics of circulating water critically influence hydrate production efficiency (Shi et al., 2024b). During hydrate-deep gas co-production, the production timing of these reservoirs alters geothermal transport dynamics by modulating reservoir temperature evolution, thereby impacting overall production performance. Consequently, optimizing production timing is essential for maximizing production efficiency. Existing studies have explored production timing strategies for combined depressurization and thermal stimulation methods: for hot water injection, high injection rates lead to thermal inefficiency and the loss of water-lock effects, which in turn results in excessive water production. To address this, a slow post-depressurization water injection technique has been proposed (Lin et al., 2023; Ye et al., 2025a; Zhang et al., 2024). Electric heating: Continuous heating exhibits low energy efficiency (Yang et al., 2016; Zhao et al., 2022a; Zhou et al., 2026); Instead, stage-specific heating aligned with production dynamics is recommended (Hou et al., 2024; Wang et al., 2026). An optimized approach includes: pre-depressurization heating to accelerate reservoir warming; heating during secondary hydrate formation to enhance dissociation; well-closure heating to sustain decomposition, followed by post-opening cessation (He et al., 2021; Sun et al., 2024). Hybrid thermal methods: To leverage the rapid heat release advantage of steam condensation and the extensive heating coverage benefit of hot water, an alternating steam-water injection strategy has been developed. This approach involves first injecting steam near the wellbore to achieve rapid hydrate dissociation, followed by hot water injection to extend the heated zone, thereby preventing localized overheating issues. (Ma et al., 2025; Zhang et al., 2025c). Sequential thermal strategies: Given the superior early-stage performance of hot water (vs. delayed electric heating effects), a hot water → electric heating sequence post-depressurization has been proposed (Wei et al., 2023; Zhao et al., 2025b). The research mentioned above provides a preliminary understanding of the production timing when using the combined method. However, there are still many challenging problems to be solved; particularly interesting is the mechanism by which the production timing of hydrate and deep gas affects the co-production characteristics. Unfortunately, there is no systematic study on this issue at present.

In this study, based on the independently-built geothermal-driven hydrate-deep gas co-production experimental platform (which is fundamentally different from the existing single-reservoir experimental devices), a systematic investigation was conducted on the coupling influence mechanism of the production timing from two reservoirs on the characteristics of the combined production and the geothermal transport. These innovative achievements not only revealed the law of the effect of time sequence regulation on enhancing the decomposition efficiency of hydrates, but also provided a new idea for the development of the

next-generation hydrate-geothermal combined production technology.

2. Experimental methodology

This section presents the experimental procedures for geothermal-assisted co-production of hydrate and deep gas, including both field tests and laboratory simulations (Section 2.1). The computational methods for energy analysis and performance evaluation are described in Section 2.2.

2.1. Recovery process description

The field test employed a dual-well system consisting of two vertical wells penetrating the hydrate layer and deep gas reservoir, respectively (Fig. 2(a)). A thermally assisted production system was implemented through engineered water circulation pipelines connecting the production platform to both reservoirs. Notably, the injection pipeline to the hydrate layer incorporated a “casing + packer” configuration to enable simultaneous water injection and return within a single wellbore (see Fig. 2(a) inset).

Laboratory simulations were conducted using two reactor vessels packed with marine sediment, deionized water, and methane gas to represent the hydrate and gas reservoirs (Fig. 2(b)). Each reactor was equipped with a vertical production well, interconnected by a water circulation system driven by a peristaltic pump. Detailed physical diagram of the experimental platform (Fig. S1), sample preparation parameters (Table S1), production schemes (Table S2), and experimental results (Table S3) are provided in the Supplementary Materials. Note: all the conclusions of this study are based on laboratory data, not on field systems. The dimensions and capacity of the reactor, as well as the position and accuracy of the sensors, have been provided in our previous work (Shi et al., 2024a). The specific details of sample preparation and production experiments in the laboratory can be found in our previous work (including sediment porosity, depressurization operations, etc.) (Shi et al., 2024c).

2.2. Energy and performance parameter calculations

The energy balance analysis considered eight distinct energy components associated with the hydrate reactor, circulating water, and ambient environment: Sensible heat of the hydrate reactor (Q_{s,C_H}); Endothermic heat of hydrate dissociation (Q_H); Gas production work ($W_{push, pro}$); Environmental heat transfer (Q_{FE}); Circulating water heat exchange (Q_{wa,C_D} , $Q_{wr,C_D \rightarrow C_H}$, Q_{wr,C_H} , and $Q_{wa,C_H \rightarrow C_D}$). The performance evaluation incorporated the water heat absorption efficiency (η_{heat} utilization of water) as a key metric. Complete derivations of energy conversion relationships and detailed calculation methodologies are available in our prior work (Shi et al., 2024c). Furthermore, the production efficiency mentioned in the discussion is the reciprocal of t_{90} .

3. Results and discussion

This section presents a comparative analysis of production performance under four distinct co-production scenarios, differentiated by the timing of deep gas production initiation: (1) simultaneous with hydrate production, (2) post-hydrate depressurization completion, and (3) with 1 or 3 h delays following hydrate production commencement. It should be noted that the production of deep gas at 1 or 3 h after the production of the hydrate layer corresponds to the early and middle stages of the constant pressure stage of the hydrate layer, respectively.

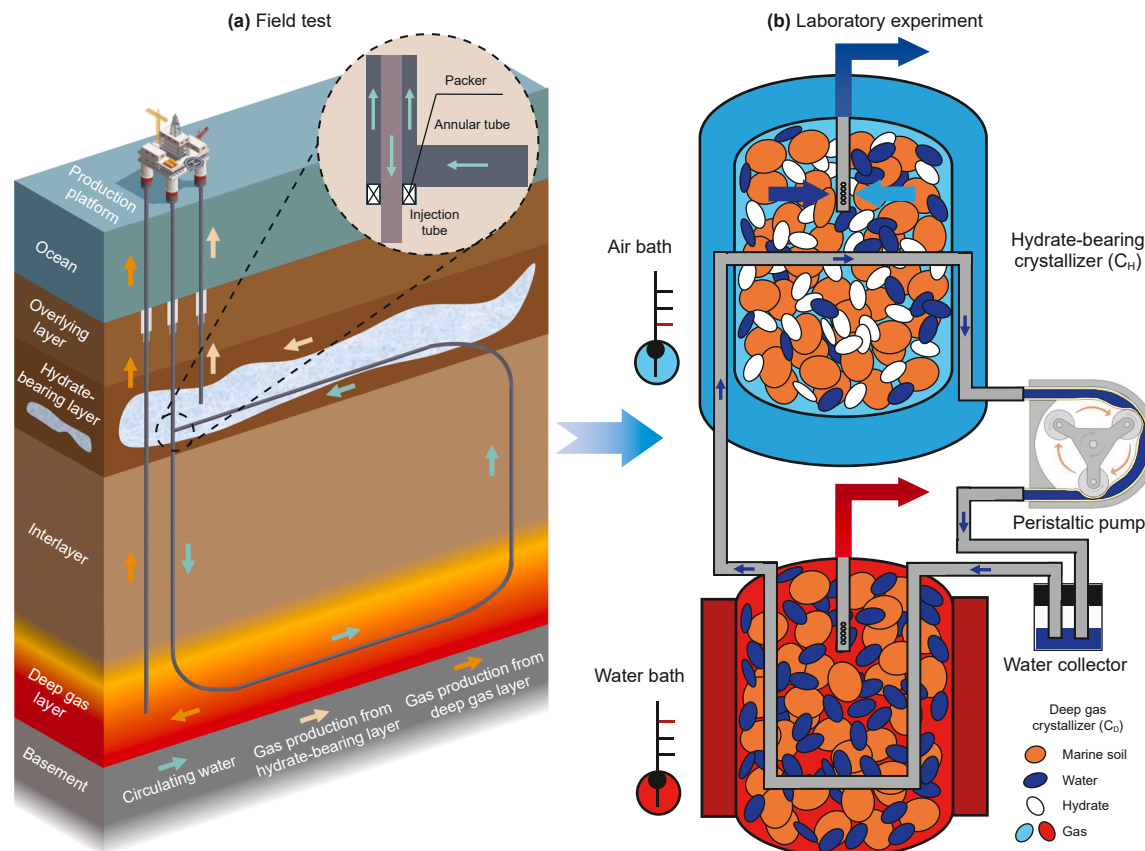


Fig. 2. Schematic diagrams of (a) field test configuration showing geothermal energy utilization through water circulation for hydrate and gas co-production, with detailed well completion design, and (b) laboratory-scale experimental setup simulating the field production process.

3.1. Production behavior of geothermal-assisted co-production of gas hydrate and deep gas

Fig. 3 illustrates the temperature evolution profiles in both hydrate and deep gas reservoirs, along with circulating water temperatures, during simultaneous geothermal-assisted production. Key observations reveal a characteristic temperature trajectory in both reservoirs, exhibiting an initial decline followed by gradual recovery. In the hydrate reservoir, the middle layer

experiences the most pronounced temperature reduction ($\Delta T_{\max} = 3.52\text{ }^{\circ}\text{C}$), while the upper layer shows the least thermal variation ($\Delta T_{\min} = 3.08\text{ }^{\circ}\text{C}$). This phenomenon results from competing thermal mechanisms: while the upper layer experiences strong Joule-Thomson cooling near the production well, the middle layer's proximity to the water circulation pipeline facilitates enhanced hydrate dissociation, leading to greater endothermic cooling. The deep gas reservoir demonstrates an inverse thermal gradient, with maximum cooling ($\Delta T_{\max} = 5.95\text{ }^{\circ}\text{C}$)

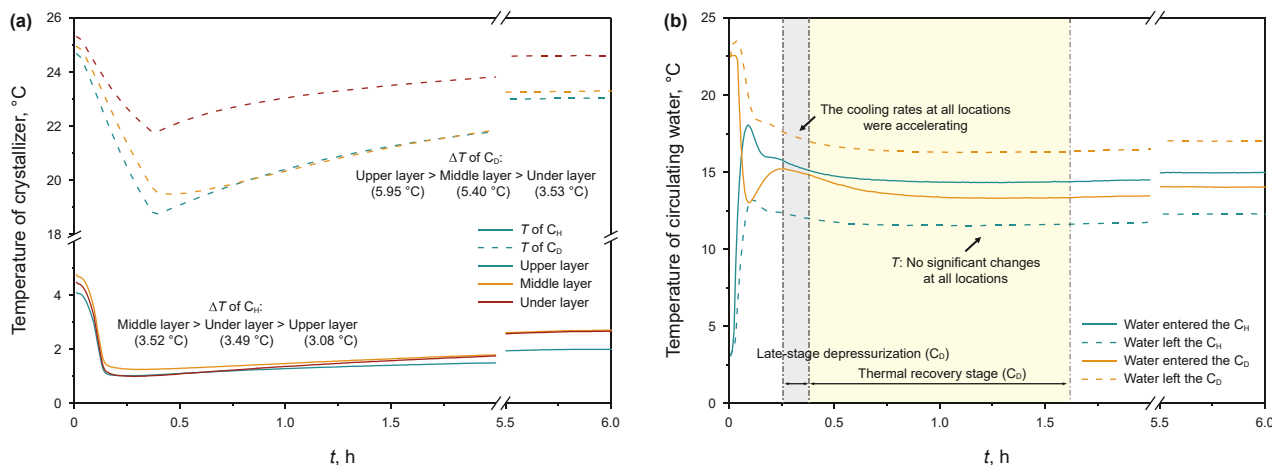


Fig. 3. Temperature evolution during geothermal-assisted co-production: (a) stratified temperature profiles in hydrate and deep gas reservoirs; (b) inlet and outlet water temperatures. Note: the co-production refers to simultaneous production from both reservoirs.

occurring in the upper production zone and minimal temperature variation in the lower layer. This spatial thermal distribution reflects both the production well positioning and reservoir heat transfer characteristics. Considering that the higher gas flow rates near the production well would trigger a more significant Joule-Thomson effect, the upper layer experiences the greatest temperature drop. In contrast, the lower layer, which is the farthest from the production well, has the lowest gas flow rate and the weakest Joule-Thomson effect, thus resulting in the smallest temperature drop. Comparative analysis reveals two fundamental differences between reservoir thermal behaviors: The deep gas reservoir exhibits slower cooling rates due to the absence of endothermic dissociation processes. Accelerated temperature recovery occurs in the deep gas reservoir, attributable to higher formation temperatures in the surrounding strata.

Water temperature evolution under co-production conditions maintains the characteristic three-phase profile observed in single-reservoir production: rapid initial change, progressive stabilization, and sustained equilibrium (see Figs. 2(b) and 3 in our previous work (Shi et al., 2024c)). However, co-production introduces distinct modifications: Enhanced cooling rates emerge during late-stage depressurization, resulting from reduced water heat absorption capacity due to sensible heat losses in the deep gas reservoir. Temperature stabilization occurs during the thermal recovery of the deep gas reservoir, where continuous hydrate decomposition maintains a heat absorption effect. This process drives the circulating water to release substantial absorbed heat, thereby preventing concurrent temperature increase with the recovering gas reservoir.

The gas production behavior exhibits distinct characteristics (Fig. 4). Three critical inflection points (A, B, C) mark the hydrate reservoir's free gas production phase: Point A: a sharp production rate increase occurs as high-velocity gas flow clears initial channel blockages. Point B: subsequent rate reduction results from particulate redeposition in production channels. Point C: gradual decline reflects both free gas depletion and diminishing pressure differential. Subsequently, the hydrate reservoir enters the hydrate decomposition gas production stage and shows the characteristic that the gas production rate gradually decreases. Based on the evolution characteristics of the gas production rate, the time-varying law of cumulative gas production in the hydrate reservoir can be deduced (that is, it increases rapidly and slowly in the

depressurization and constant pressure phases, respectively, see the inset (a) in Fig. 4). It should be noted that the t_{90} of the hydrate reservoir under co-production conditions was 6.19 h, which was 12.60% higher than 6.97 h under single production conditions (see Table 1 in our previous work (Shi et al., 2024c)). This is due to the enhanced heat exchange between the water and the deep gas reservoir in the co-production, which enables more heat to be transported by the water to the hydrate reservoir. A similar phenomenon has been confirmed in our previous work (Yang et al., 2025).

The gas production dynamics of deep gas reservoirs differ fundamentally from hydrate reservoirs, exhibiting two key distinctions: 1) Stable production phase: after an initial rapid increase, the gas production rate stabilizes for an extended duration. Sustained low-amplitude oscillations during this phase arise from intermittent blockage and clearance of gas flow channels due to high-velocity particulate transport. 2) Termination at constant pressure: deep gas production ceases upon entering the constant-pressure phase, unlike hydrate reservoirs where dissociation-driven production persists (see the inset (b) in Fig. 4). Notably, the deep gas reservoir achieves t_{90} in 0.33 h—an order of magnitude faster than the hydrate reservoir ($t_{90} = 6.19$ h). This efficiency stems from the absence of endothermic dissociation processes. Strategically, deep gas production can thus be timed to optimize geothermal heat transport, enhancing hydrate production efficiency.

The energy conversion characteristics within the system were presented in Fig. 5 up to 6 h, using the hydrate reactor and water as the thermal system. It can be observed that although 166.73 kJ of geothermal energy was transported by water to the hydrate decomposition process, most of the energy required for hydrate decomposition still originated from heat transfer from the surrounding strata (up to 944.07 kJ). This phenomenon reveals the bottleneck of the current geothermal transport efficiency: significant heat loss occurs during the pipeline transportation of hot water from the deep gas layer to the hydrate layer. To address this issue, this study drew on the insulation technology of deep-sea oil and gas pipelines and aimed to minimize the heat loss rate by using multiple layers of polyethylene materials. Additionally, the heat absorbed by water during its transportation from the hydrate reservoir to the deep gas reservoir (116.59 kJ) was at the same level as the heat absorbed by water in the deep gas reservoir (177.73 kJ).

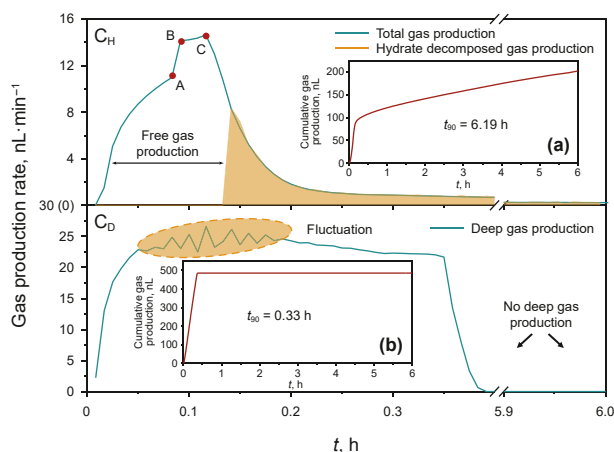


Fig. 4. Time-varying characteristics of instantaneous gas production rates in hydrate reservoirs and deep gas reservoirs during geothermal-assisted co-production. The time-varying characteristics of cumulative gas production in the two reservoirs are presented in insets (a) and (b), respectively. Note: Here, the co-production refers to simultaneous production from both reservoirs.

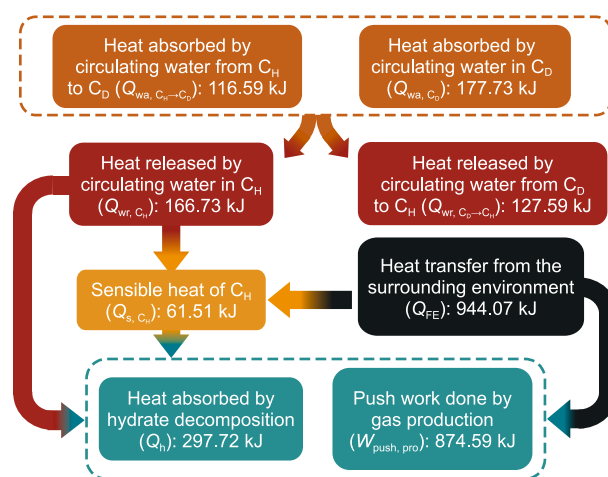


Fig. 5. Energy conversion within the thermal system up to 6 h (with hydrate reservoirs and circulating water as the thermal system). Note: the area of the pattern corresponding to each type of energy reflects the magnitude of the energy, but this is not drawn in proportion to the energy.

Similar situations still exist during the exothermic process, indicating that by optimizing the coordinated design of pipeline insulation and heat extraction from the strata, the gap between the two can be further narrowed. This result verifies the importance of appropriate heat extraction from the strata and highlights the key role of pipeline insulation technology in achieving the multi-win goal of “utilizing the geothermal gradient to increase heat absorption, shortening drilling depth and reducing heat transport losses”.

In summary, the geothermal-assisted hydrate-deep gas co-production accelerates the rate of water temperature drop, enhances the heat exchange intensity between water and deep gas reservoirs, and ultimately increases the production efficiency of hydrate reservoirs by 12.60% compared to the situation of geothermal assisted hydrate production alone. In addition, the production of gas from deep gas reservoirs is highly efficient because there is no hydrate decomposition stage. Therefore, utilizing the mechanism of deep gas production on geothermal transport to enhance the efficiency of hydrate reservoir production is an important basis for determining the timing of deep gas reservoir production.

3.2. Strategy 1: producing the deep gas after completing the hydrate depressurization stage

The above work confirms the negative impact of producing deep gas reservoirs on water temperature. In order to increase the temperature of water as much as possible during the depressurization stage of the hydrate reservoir, thereby promoting more hydrate decomposition during this stage. This study conducted a co-production scheme for deep gas reservoirs after depressurization of the hydrate reservoir (Case 2). The production results are shown in Fig. 6. It can be seen that the production efficiency of the hydrate reservoir in Case 2 was 6.79% higher than that in Case 1. At the same time, the production efficiency of the deep gas reservoirs in both cases was nearly identical, which not only verified the effectiveness of the new co-production scheme in promoting hydrate decomposition but also indicated a weak correlation between the timing of deep gas production and its production rate. Further analysis of the stage hydrate decomposition rate revealed that, in Case 2, the rate during depressurization did not increase as expected; instead, it decreased significantly. In the constant-pressure phase, the hydrate decomposition rate in Case 2 increased by 0.71% compared to Case 1, which ultimately led to an

increase in production efficiency. The reasons for the evolution of the hydrate decomposition rate will be explained in combination with the temperature evolution characteristics of the two reservoirs and water during the production process (see Fig. 7).

The temperature drop in each layer of the hydrate reservoir in Case 2 was different from that in Case 1 (see Fig. 7(a)). Further analysis of the evolution of water temperature revealed that during the depressurization phase of the hydrate reservoir, the new co-production method did indeed increase the average water temperature in both reservoirs (see points A, B, and C in Fig. 7(b)). However, the temperature drop in the hydrate reservoir induced by the high-temperature water still increased, and the hydrate decomposition rate decreased significantly during this stage, indicating that there was almost no blockage in the pore channels when free gas was produced, and then a more pronounced Joule-Thomson effect occurred. In addition, the preferential production of free gas also restricts the diffusion and migration of gas from hydrate decomposition during the same period, thereby weakening the hydrate decomposition rate during the depressurization stage. When the production enters the early stage of the constant-pressure phase of the hydrate reservoir, it can be observed that the average temperature of water in Case 2 in both reservoirs is higher than that in Case 1, which is related to the fact that the deep gas reservoir has just begun production and the reservoir temperature has not dropped significantly at this time. The higher-temperature water enters the hydrate reservoir and has a greater temperature difference with the reservoir, which not only helps to enhance the heat exchange intensity between the water and the reservoir, but also enables the heat released by the water to spread over a wider range, thereby promoting the rapid hydrate decomposition (see Fig. 7(c) and (d)). It should be noted that the rapid hydrate decomposition also absorbs more geothermal energy, ultimately increasing the temperature drop in the deep gas reservoir. When the production enters the warming stage of the deep gas reservoir, the water temperature in Case 2 does not increase accordingly, similar to the evolution of the water temperature in Case 1. The continuous hydrate decomposition for heat absorption is also the main reason why the water temperature in Case 2 has not risen.

In summary, producing the deep gas reservoirs after the depressurization of hydrate reservoirs increases the temperature of water in the early stage of the constant-pressure phase, intensifies the heat exchange intensity between water and hydrate reservoirs, expands the influence range of heat released by water in hydrate reservoirs, and ultimately increases the production efficiency of hydrate reservoirs by 6.79%.

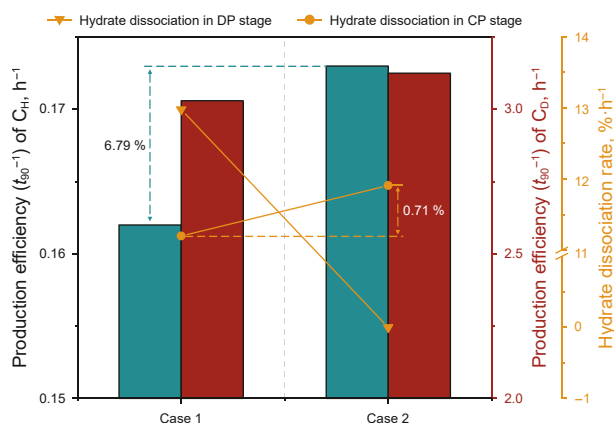


Fig. 6. Comparison of production efficiency of hydrate reservoirs and deep gas reservoirs in Cases 1 and 2 (bar chart). Comparison of hydrate decomposition rates during depressurization and constant-pressure phases in the two cases (dot plot).

3.3. Strategy 2: producing the deep gas 1 h after hydrate production

The experimental results in Section 3.2 validate the positive effect of high-temperature water at constant-pressure phase on enhancing hydrate decomposition. To extend the duration of this effect, the production time of the deep gas reservoir in this section was delayed by 1 h after the hydrate reservoir production (Case 3). The production results are shown in Fig. 8. The entire production process is divided into three production nodes of 0.5, 1.0, and 3.0 h according to the depressurization phase, the early, middle, and late stages of the constant-pressure phase of the hydrate reservoir, with a total of four production stages. It can be found that the amount and rate of hydrate decomposition in Cases 2 and 3 are basically the same at each production stage, indicating that delaying the production timing of deep gas reservoirs is difficult to enhance the hydrate decomposition rate. The specific reasons will be explained in the discussion below.

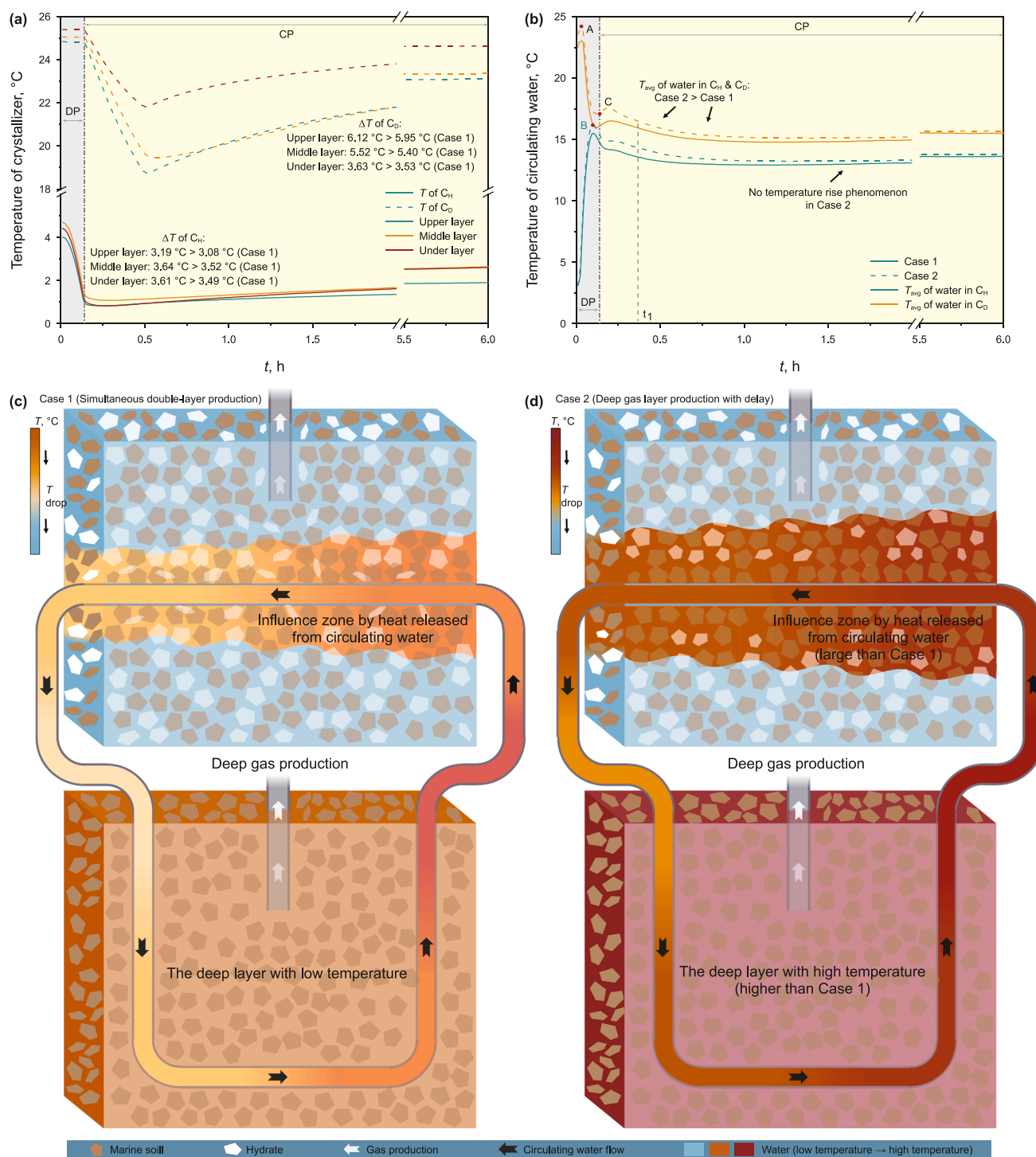


Fig. 7. (a) Time-varying temperature characteristics of each layer of the hydrate reservoir and deep gas reservoir in Cases 1 and 2. (b) Time-varying characteristics of the average temperature of water in both cases in the two reservoirs. Schematic diagram of the heat transfer of water in the two reservoirs at time t_1 and its effect on hydrate decomposition (c and d). Note: time t_1 is indicated in (b).

The time-varying characteristics of the water average temperature in the two reservoirs of Cases 2 and 3 are presented in Fig. 9(a). It can be observed that during the 0–0.5 h stage, the water temperatures in the two cases were basically the same, and thus the hydrate decomposition characteristics were similar at this time (see Fig. 8). When entering the 0.5–1.0 h stage, the average water temperature in Case 2 is lower than that in Case 3, which is related to the decrease in temperature of the deep gas reservoir in

Case 2 due to its own gas production at this time. At this point, the hydrates in each layer of Case 3 receive more heat from the release of water, which is conducive to promoting the hydrate decomposition (see Fig. 9(b)). However, during the production of the deep gas reservoir in Case 3, the water temperature began to drop rapidly (see the A–B stage in Fig. 9(a)), and in some cases it was lower than in Case 2 (the B–C stage). This led to a rapid decline in the heat that had stimulated hydrate decomposition in Case 3,

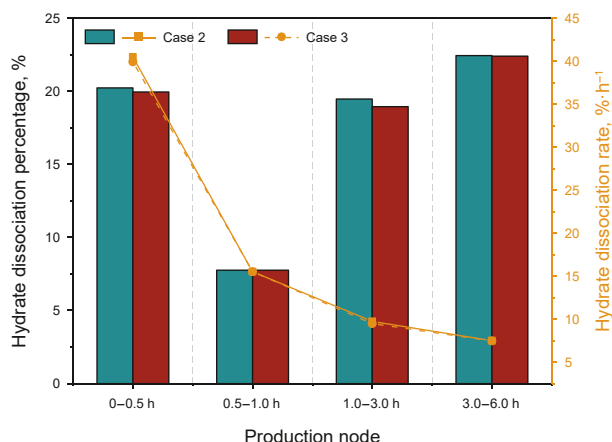


Fig. 8. Comparison of the hydrate decomposition at various production stages in Cases 2 and 3 (bar chart). Comparison of the hydrate decomposition rates at various production stages in the two cases (dot plot). Note: the entire production process is divided into four stages based on three production nodes: 0.5, 1.0 and 3.0 h.

which could not sustain sustained and efficient hydrate decomposition. Therefore, the hydrate decomposition characteristics at each production stage in Case 3 are not significantly different from those in Case 2.

In summary, delaying the production time of deep gas reservoirs to the early stage of the constant-pressure phase of the hydrate reservoir is beneficial for further prolonging the effect time of high-temperature water on hydrate decomposition. However, due to the short duration of the action, the hydrate decomposition characteristics did not change significantly.

3.4. Strategy 3: producing the deep gas 3 h after hydrate production

Considering that in Section 3.3, the production of deep gas in the early stage of the constant-pressure phase of the hydrate reservoir is not conducive to the continuous exothermic release of high-temperature water to promote hydrate decomposition. In Case 4, the production of deep gas was further delayed by 3 h after the hydrate reservoir was produced to make fuller use of geothermal energy for rapid hydrate decomposition. The production results are shown in Fig. 10. It can be observed that the

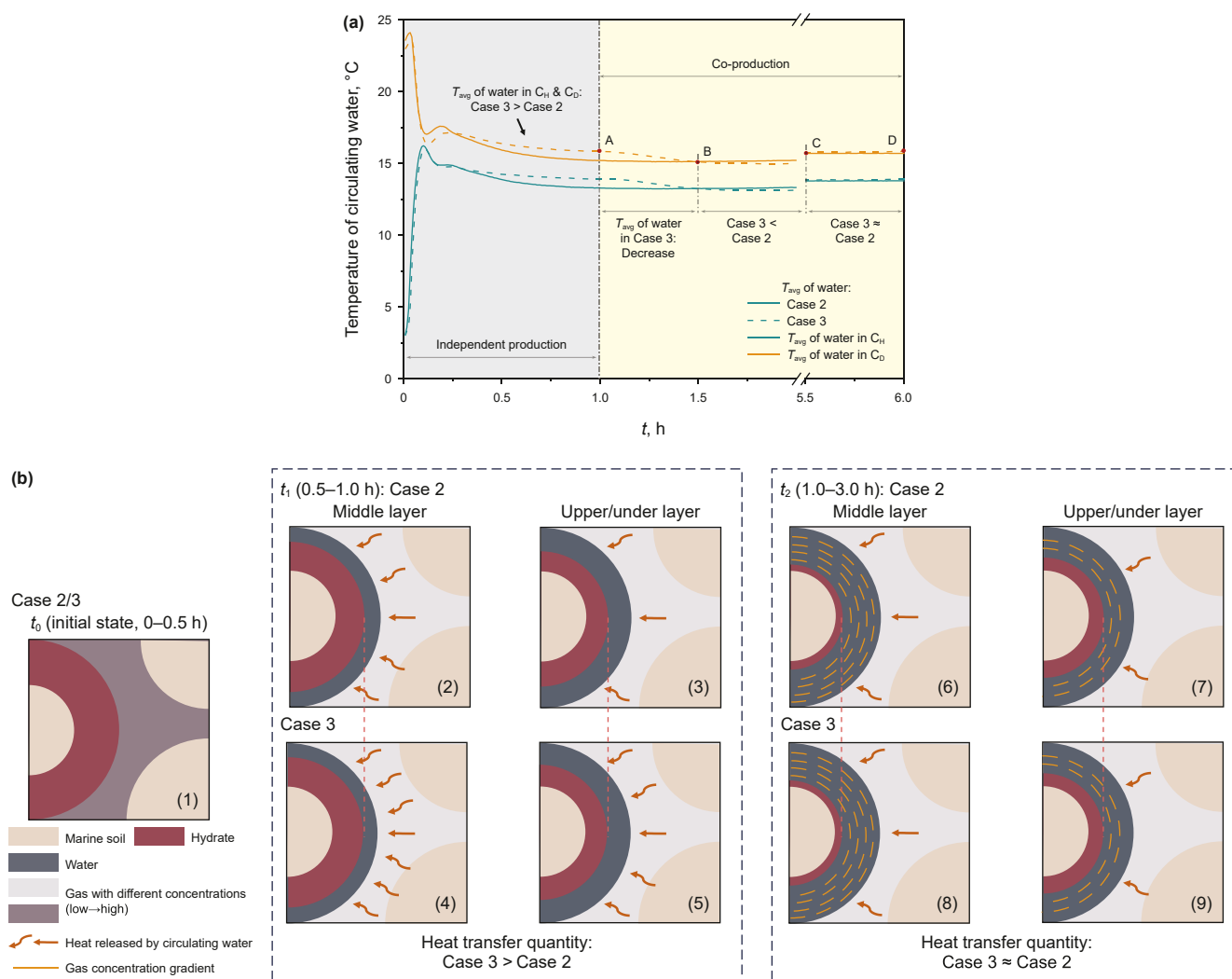


Fig. 9. (a) Time-varying characteristics of average temperature of water in hydrate reservoirs and deep gas reservoirs in Cases 2 and 3. (b) Schematic diagrams of the hydrate decomposition in the pores of each layer of the reservoirs in the two cases under the effect of exothermic water. t_0 , t_1 , and t_2 correspond to the initial time of the hydrate reservoir exploitation, the early stage of the constant pressure phase (0.5–1.0 h), and a certain time in the middle stage of the constant pressure phase (1.0–3.0 h).

amount and rate of hydrate decomposition in Case 4 at each production stage are higher than those in Case 2, suggesting that extending the duration of high-temperature water can accelerate the hydrate decomposition. In particular, during the 1.0–3.0 h phase, the increase in the amount of hydrate decomposition in Case 4 was the greatest. In addition, as production progresses to the 3.0–6.0 h stage, the difference in hydrate decomposition rate between the two cases are minimal. The specific reasons will be explained in the discussion below.

The time-varying characteristics of water temperature in the two reservoirs of Cases 2 and 4 are shown in Fig. 11(a). It can be observed that delaying the production time of deep gas reservoirs further prolongs the duration of high-temperature water. By comparing the time-varying characteristics of water temperature in Cases 3 and 4, it was found that during the 0.5–1.0 h stage, the water transfer heat received by hydrates at each layer was basically the same in both (see Figs. 9(b) and 11(b)); But the difference occurred in the 1.0–3.0 h stage: when the high-temperature water in Case 4 was still circulating continuously in the hydrate reservoir, which allowed the heat release from the water to be continuously transferred to the hydrate, thereby stimulating the continuous hydrate decomposition. The increase in the amount of hydrate decomposition was most significant during this stage (see Fig. 10). In addition, the water temperature in Cases 3 and 4 was decreasing when the two reservoirs were co-produced (see the A–B stage in Figs. 9(a) and 11(a)). Interestingly, in the subsequent production phase (the B–C stage), the water temperature in Case 4 was even higher than that in Case 2, which did not occur in the experimental results of Case 3. The reason for this result is that at this time, there is less undecomposed hydrate remaining in Case 4 than in Cases 2 and 3, which causes less heat loss of water in the hydrate reservoir and a faster rate of temperature increase.

In summary, delaying the production of deep gas reservoirs to the middle of the constant-pressure stage of the hydrate reservoir can effectively prolong the duration of heat release from high-temperature water into the hydrate reservoir, leading to a significant increase in the hydrate decomposition rate during this stage.

Finally, the co-production method used in Cases 1–4 is shown in Fig. 12(a). The performance of all cases in terms of production efficiency, reservoir temperature drop, and heat utilization from water transport is shown in Fig. 12(b). This study sets the maximization of hydrate production efficiency as the primary optimization goal (this is a key indicator determining the commercial

feasibility), while also taking into account the secondary consideration of thermal energy utilization efficiency. It should be noted that production efficiency and reservoir temperature drop are summarized separately for the hydrate reservoir and the deep gas reservoir. It can be seen that, in terms of the production efficiency of the hydrate reservoir, delaying the production timing of the deep gas reservoir enhances the hydrate production efficiency. In particular, in Case 4, the production efficiency was 17.28% higher than that in Case 1. In terms of the production efficiency of the deep gas reservoirs, the efficiency of all cases fluctuated between of 2.9 and 3.3 h⁻¹, indicating that the production efficiency of deep gas reservoirs was minimally affected by production timing and the production performance of the hydrate reservoir. In addition, regarding the temperature drop range in hydrate reservoirs, Case 4 had the largest temperature drop and Case 1 had the smallest, which was related to the increased sensible heat loss of the reservoir due to the accelerated hydrate decomposition rate. In terms of the temperature drop in deep gas reservoirs, it was found that gradually delaying the production timing of deep gas reservoirs lowered the minimum temperature. The reason for this result is that the delayed production time requires the deep gas reservoir to provide more heat during the single hydrate production stage. Furthermore, in terms of the utilization ratio of heat transport, Case 2 has the highest ratio and Case 4 has the lowest, indicating that the utilization ratio of heat transport is lower during the single hydrate production stage. Long periods of single exploitation can have a significant negative impact on the heat transfer utilization. It should be noted that although Case 4 achieves the highest production efficiency, its thermal energy utilization rate is relatively low. This indicates that in practical applications, a balance between production capacity and energy efficiency needs to be sought based on specific requirements (such as energy prices, equipment costs, etc.). For regions with abundant geothermal resources, Case 4 can be given priority; while for areas with limited energy supply, Case 2 may have a more comprehensive advantage.

Although this study systematically revealed the mechanism by which the production timing affects the efficiency of the combined production of hydrates and deep gas, it still has certain limitations and provides directions for further research: 1) Limitations of experimental scale: this study was based on laboratory-scale simulation experiments, which could precisely control variables and reveal the mechanism. However, the geological conditions of actual reservoirs (such as heterogeneity, permeability variations, multiphase flow coupling, etc.) may affect the applicability of the extraction timing strategy. Future research can combine numerical simulation or field tests to verify the economic and feasibility of this strategy in real reservoirs. 2) Simplification of geological conditions: The laboratory-prepared reservoirs have an ideal homogeneous structure, while actual reservoirs may contain complex geological structures (such as faults, fractures, interlayers, etc.). These factors may affect the efficiency of geothermal transport and the optimization of production timing. Future research can explore the adaptability of production timing strategies under different geological conditions and study how to combine reservoir engineering to optimize the plan. 3) Economic and engineering challenges: Although the experiment proved that producing deep gas during the constant pressure stage can increase efficiency by 10.49%, economic factors such as drilling costs, insulation technology, and energy consumption of the circulating water system need to be considered in practical applications. Future research can conduct technical and economic evaluations to optimize the balance point between production timing and engineering implementation, in order to enhance the commercial potential. 4) Coupling optimization of multiple factors: This study

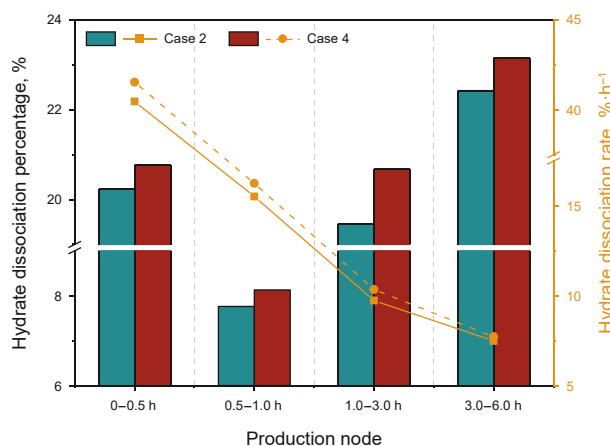


Fig. 10. Comparison of the hydrate decomposition amounts in Cases 2 and 4 at various production stages (bar chart). Comparison of the hydrate decomposition rates at various production stages in the two Cases (dot plot). Note: the entire production process is divided into four stages based on three production nodes: 0.5, 1.0 and 3.0 h.

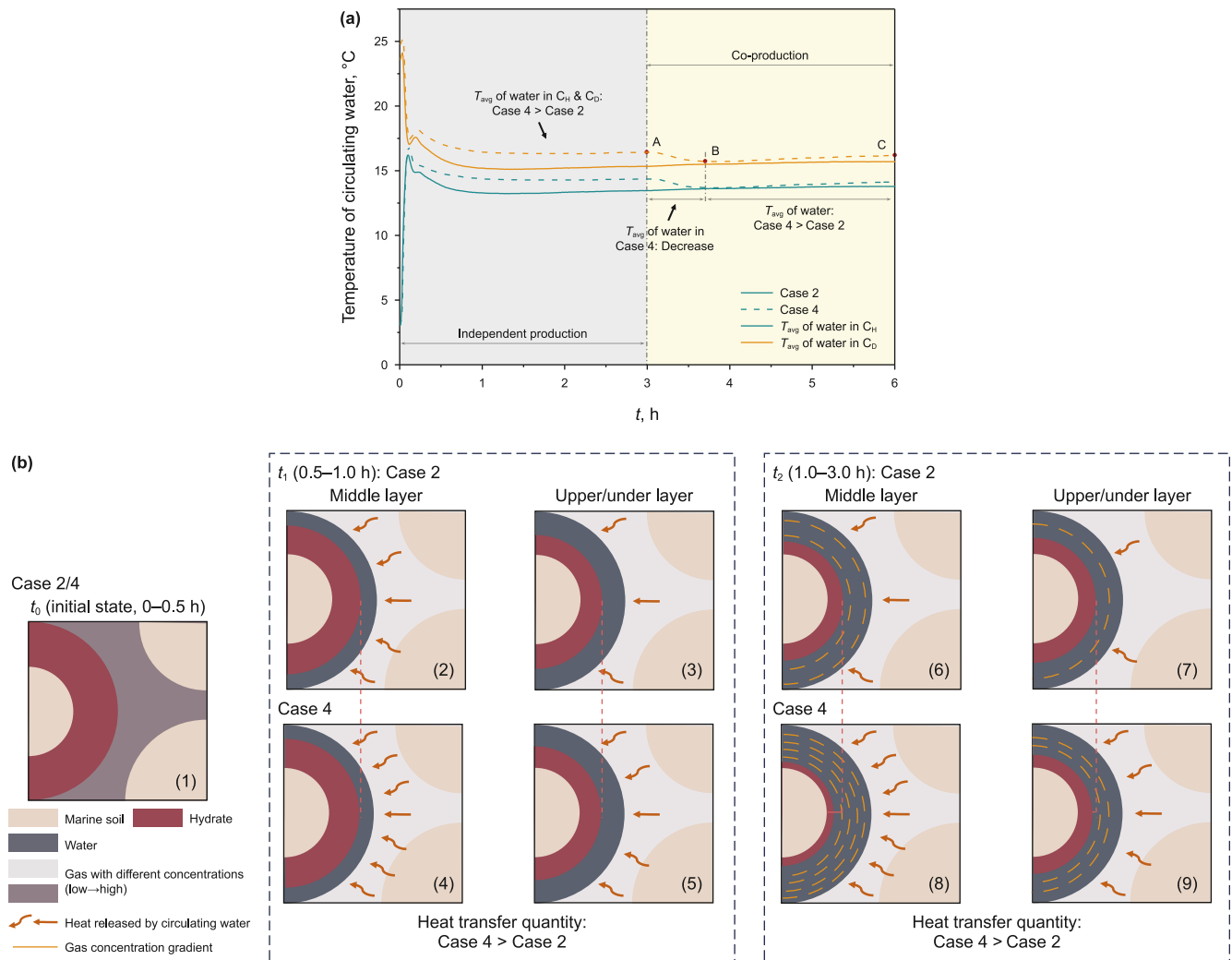


Fig. 11. (a) Time-varying characteristics of the average water temperature in the hydrate reservoirs and the deep gas reservoir in Cases 2 and 4. (b) Schematic diagrams of the hydrate decomposition in the pores of each layer of the reservoirs in the two cases under the effect of exothermic water. t_0 , t_1 , and t_2 correspond to the initial time of the hydrate reservoir production, the early stage of the constant-pressure phase (0.5–1.0 h), and a certain time in the middle stage of the constant-pressure phase (1.0–3.0 h).

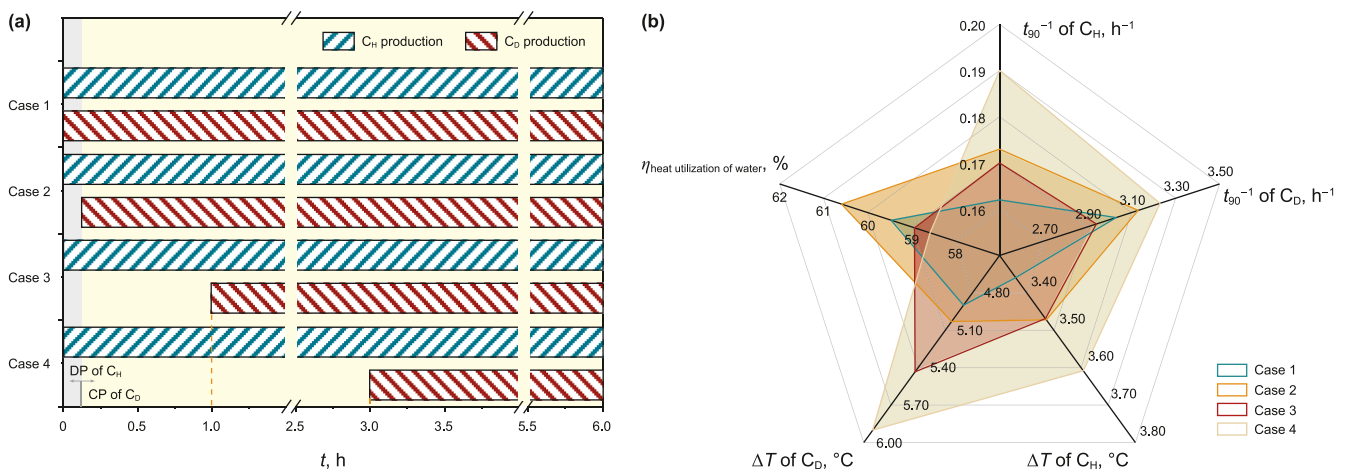


Fig. 12. (a) Summary of the hydrate-deep gas co-production method used in Cases 1 to 4. (b) Summary of the performance of all cases in terms of production efficiency, reservoir temperature drop range, and heat transfer utilization ratio of water.

focused on the influence of production timing, but actual production may involve the synergy of multiple factors (such as heat injection methods, depressurization rates, reservoir modification, etc.). Future research can combine intelligent optimization algorithms (such as machine learning, genetic algorithms) to explore multi-parameter coordinated control strategies to further improve production efficiency. In summary, this study provides important theoretical basis and experimental support for the combined production of hydrates and deep gas. In the future, it can be combined with numerical simulation, field tests, and economic analysis to promote the technology towards engineering application.

4. Conclusions

This study systematically investigated the influence of production sequencing on the co-production characteristics of hydrate and deep gas reservoirs, with particular emphasis on optimizing hydrate decomposition efficiency by strategically timing deep gas production. The key findings are summarized as follows:

- (1) Geothermal-assisted co-production of hydrate and deep gas reservoirs improves hydrate recovery efficiency by 12.60% compared to standalone geothermal-assisted hydrate production. The high production efficiency of deep gas reservoirs (without hydrate dissociation) highlights the importance of optimizing production timing to enhance geothermal heat transfer and boost hydrate production.
- (2) Initiating deep gas production following hydrate reservoir depressurization elevates water temperature during the early constant-pressure phase. This thermal enhancement intensifies heat exchange between water and the hydrate reservoir, extends the spatial influence of heat diffusion, and ultimately increases hydrate production efficiency by 6.79%.
- (3) Postponing deep gas production to the early constant-pressure phase of hydrate extraction prolongs the thermal stimulation effect of high-temperature water on hydrate dissociation. However, the short-term behavior of this thermal contribution results in only marginal improvements in decomposition dynamics.
- (4) Further delaying deep gas production to the mid-constant-pressure phase significantly extends the duration of heat transfer from high-temperature water to the hydrate reservoir, leading to a marked acceleration in hydrate decomposition rates during this stage. Comparative analysis across all experimental cases confirms that optimized timing of deep gas production improves overall production efficiency.

These findings provide critical insights for designing efficient co-production strategies in hybrid hydrate-gas systems, emphasizing the importance of thermal management and production sequencing to maximize energy recovery.

CRedit authorship contribution statement

Kang-Ji Shi: Writing – original draft, Funding acquisition, Data curation, Conceptualization. **Yan-Long Li:** Formal analysis. **Yong-Chao Zhang:** Investigation, Funding acquisition. **Yun-Kai Ji:** Methodology, Funding acquisition. **Sheng-Biao Liu:** Resources, Funding acquisition. **Zhi-Wen Sun:** Software. **Lei Yang:** Writing – review & editing, Supervision, Funding acquisition. **Gao-Wei Hu:** Writing – review & editing, Supervision, Funding acquisition. **Chang-Ling Liu:** Supervision. **Yong-Chen Song:** Validation,

Funding acquisition. **Neng-You Wu:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.petsci.2026.04.035>.

References

- Anderson, B.J., et al., 2011. Regional long-term production modeling from a single well test, Mount Elbert gas hydrate stratigraphic test well, Alaska north slope. *Mar. Petrol. Geol.* 28 (2), 493–501. <https://doi.org/10.1016/j.marpetgeo.2010.01.015>.
- Cai, J., et al., 2025. Pore-scale investigation of forced imbibition in porous rocks through interface curvature and pore topology analysis. *J. Rock Mech. Geotech. Eng.* 17 (1), 245–257. <https://doi.org/10.1016/j.jrmge.2024.02.047>.
- Chen, M., et al., 2023. Recent advances in creep behaviors characterization for hydrate-bearing sediment. *Renew. Sustain. Energy Rev.* 183, 113434. <https://doi.org/10.1016/j.rser.2023.113434>.
- Chen, Q., et al., 2020. Dissociation kinetics characteristics of nodular methane hydrates and their influence factors. *Nat. Gas. Ind.* 40 (8), 141–148. <https://doi.org/10.3787/j.issn.1000-0976.2020.08.011>.
- Chen, X., et al., 2022. Developing offshore natural gas hydrate from existing oil & gas platform based on a novel multilateral wells system: depressurization combined with thermal flooding by utilizing geothermal heat from existing oil & gas wellbore. *Energy* 258, 124870. <https://doi.org/10.1016/j.energy.2022.124870>.
- Cheng, F., et al., 2023. Numerical analysis of coupled thermal-hydro-chemo-mechanical (THCM) behavior to joint production of marine gas hydrate and shallow gas. *Energy* 281, 128224. <https://doi.org/10.1016/j.energy.2023.128224>.
- Cozzi, L., et al., 2025. *Global Energy Review 2025*. International Energy Agency, France.
- Fan, J., et al., 2025. A novel viscoplastic model for salt rock deformation under internal cyclic gas pressure loading. *Int. J. Min. Sci. Technol.* 35 (6), 989–1004. <https://doi.org/10.1016/j.ijmst.2025.05.005>.
- Feng, Y., et al., 2024. Study of hydrate nucleation and growth aided by micro-nanobubbles: probing the hydrate memory effect. *Energy* 290, 130228. <https://doi.org/10.1016/j.energy.2023.130228>.
- Gong, B., et al., 2025. Mitigating risks in deep sea gas hydrate production: a new perspective on interpreting thermo-hydro-mechanical feedbacks. *Adv. Geo-Energy Res.* 17 (3), 267–270. <https://doi.org/10.46690/ager.2025.09.08>.
- He, J., et al., 2021. Combined styles of depressurization and electrical heating for methane hydrate production. *Appl. Energy* 282, 116112. <https://doi.org/10.1016/j.apenergy.2020.116112>.
- He, J., et al., 2022. Sustainable hydrate production using intermittent depressurization in hydrate-bearing reservoirs connected with water layers. *Energy* 238, 121752. <https://doi.org/10.1016/j.energy.2021.121752>.
- Hou, J., et al., 2024. Numerical simulation of gas production from class III hydrate reservoirs using low-frequency electric heating-assisted depressurization with horizontal wells. *Fuel* 357, 129906. <https://doi.org/10.1016/j.fuel.2023.129906>.
- Hu, G., et al., 2024. Formation mechanism and geophysical properties of fracture-filling gas hydrate in the host sediments: a comprehensive review. *Earth Sci. Rev.* 258, 104917. <https://doi.org/10.1016/j.earscirev.2024.104917>.
- Hussain, A., et al., 2017. Emerging renewable and sustainable energy technologies: state of the art. *Renew. Sustain. Energy Rev.* 71, 12–28. <https://doi.org/10.1016/j.rser.2016.12.033>.

- Ji, Y., et al., 2026. Evolution characteristics of pore water during methane hydrate dissociation by depressurization in unconsolidated sand. *Int. J. Hydrogen Energy* 197, 152582. <https://doi.org/10.1016/j.ijhydene.2025.152582>.
- Jiang, Z., et al., 2025. Pronounced thermodynamic inhibitory effect of clay-bound water on CO₂ hydrate formation: underlying mechanisms and mitigation strategies towards CO₂ sequestration. *Chem. Eng. J.* 523, 168760. <https://doi.org/10.1016/j.cej.2025.168760>.
- Jin, G., et al., 2024. Gas production from a promising reservoir of the hydrate with associated and shallow gas layers in the low permeable sediments. *Energy* 295, 131079. <https://doi.org/10.1016/j.energy.2024.131079>.
- Kim, H.C., et al., 1987. Kinetics of methane gas hydrate decomposition. *Chem. Eng. Sci.* 42 (7), 1645–1653. [https://doi.org/10.1016/0009-2509\(87\)80169-0](https://doi.org/10.1016/0009-2509(87)80169-0).
- Kou, Y., et al., 2023. Macroscale insights into heterogeneous hydrate formation and decomposition behaviors in porous media. *Chem. Eng. J.* 475, 146215. <https://doi.org/10.1016/j.cej.2023.146215>.
- Li, Y., et al., 2024. Time-dependent deformation of marine gas hydrate-bearing strata conditioned to a wellbore: experiments and implications. *Ocean. Eng.* 308, 118220. <https://doi.org/10.1016/j.oceaneng.2024.118220>.
- Li, Y., et al., 2023. Experimental study on solid particle migration and production behaviors during marine natural gas hydrate dissociation by depressurization. *Pet. Sci.* 20 (6), 3610–3623. <https://doi.org/10.1016/j.petsci.2023.05.018>.
- Li, Y., et al., 2026. Stress-induced melting controlled failure mechanisms of methane hydrate. *Adv. Sci.* 13 (10), e18367. <https://doi.org/10.1002/advs.202518367>.
- Lin, D., et al., 2023. Numerical study on natural gas hydrate production by hot water injection combined with depressurization. *Energy* 282, 128862. <https://doi.org/10.1016/j.energy.2023.128862>.
- Liu, Y., et al., 2020. A novel natural gas hydrate recovery approach by delivering geothermal energy through dumphlooding. *Energy Convers. Manag.* 209, 112623. <https://doi.org/10.1016/j.enconman.2020.112623>.
- Liu, Y., et al., 2018. A method to recover natural gas hydrates with geothermal energy conveyed by CO₂. *Energy* 144, 265–278. <https://doi.org/10.1016/j.energy.2017.12.030>.
- Liu, Y., et al., 2019. Numerical simulation of simultaneous exploitation of geothermal energy and natural gas hydrates by water injection into a geothermal heat exchange well. *Renew. Sustain. Energy Rev.* 109, 467–481. <https://doi.org/10.1016/j.rser.2019.04.049>.
- Ma, H., et al., 2025. Changes in the effective absolute permeability of hydrate-bearing sands during isotropic loading and unloading. *Pet. Sci.* 23 (2), 998–1013. <https://doi.org/10.1016/j.petsci.2025.10.009>.
- Ma, S., et al., 2024. Natural gas hydrate decomposition characteristics at the exploitation anaphase via sediment warming. *Energy Fuel.* 38 (15), 14334–14342. <https://doi.org/10.1021/acs.energyfuels.4c02709>.
- Niu, M., et al., 2023. CH₄ hydrate production coupled with CO₂ sequestration and hydrate restoration employing depressurization assisted by CO₂-N₂ injection at marine conditions. *Chem. Eng. J.* 456, 140981. <https://doi.org/10.1016/j.cej.2022.140981>.
- Qin, X., et al., 2025. Pore-scale investigation of water-CO₂-oil flow in shale fractures for enhanced displacement efficiency and CO₂ sequestration. *Eng. Geol.* 348, 107969. <https://doi.org/10.1016/j.enggeo.2025.107969>.
- Qiu, X., et al., 2026. Evolution characteristics of methane concentration and microscopic formation mechanisms of methane hydrate: insights from in-situ Raman spectroscopy. *Gas Sci. Eng.* 146, 205818. <https://doi.org/10.1016/j.jgsce.2025.205818>.
- Shi, K., et al., 2024a. Enhancing gas hydrate decomposition assisted by the shallow gas: effects of interlayer permeability and depressurization strategies. *Fuel* 374, 132477. <https://doi.org/10.1016/j.fuel.2024.132477>.
- Shi, K., et al., 2024b. Experimental analysis of the hydrate dissociation assisted by the deep gas heat transported through the circulating water. *Geoenery Sci. Eng.* 242, 213205. <https://doi.org/10.1016/j.geoen.2024.213205>.
- Shi, K., et al., 2024c. Strengthening the energy efficiency ratio of warm deep gas-assisted hydrate production through optimizing water circulation. *Chem. Eng. J.* 497, 154335. <https://doi.org/10.1016/j.cej.2024.154335>.
- Sohn, Y., et al., 2024. Geomechanical responses of sand-clay interbedded gas hydrate-bearing deposits under depressurization-driven gas production at site UBGH2-6 in Ullung Basin, offshore Korea. *Gas Sci. Eng.* 126, 205337. <https://doi.org/10.1016/j.jgsce.2024.205337>.
- Song, X., et al., 2018. Numerical simulation of heat extraction performance in enhanced geothermal system with multilateral wells. *Appl. Energy* 218, 325–337. <https://doi.org/10.1016/j.apenergy.2018.02.172>.
- Sun, X., et al., 2024. Optimized dual-gas co-production from hydrate reservoirs with underlying gas through depressurization & well closure cycling: an experimental evaluation. *Chem. Eng. J.* 489, 151266. <https://doi.org/10.1016/j.cej.2024.151266>.
- Wang, K., et al., 2026. Influence of pore-water salinity on the permeability of hydrate-bearing clayey sediments under isotropic and one-dimensional compression: a theoretical model. *Comput. Geotech.* 192, 107871. <https://doi.org/10.1016/j.compgeo.2025.107871>.
- Wang, T., et al., 2025. Synergistic improvement of CH₄ recovery and CO₂ sequestration via CH₄/CO₂ replacement assisted by optimizing stratigraphic mass transfer environment. *Fuel* 385, 134182. <https://doi.org/10.1016/j.fuel.2024.134182>.
- Wei, R., et al., 2022. Long-term numerical simulation of a joint production of gas hydrate and underlying shallow gas through dual horizontal wells in the South China Sea. *Appl. Energy* 320, 119235. <https://doi.org/10.1016/j.apenergy.2022.119235>.
- Wei, W., et al., 2023. Investigating optimal thermal-assisted depressurization regimes for enhanced methane hydrate dissolution in a multiple well system. *Energy Fuel.* 37 (20), 15795–15807. <https://doi.org/10.1021/acs.energyfuels.3c03115>.
- Yamamoto, K., et al., 2014. In: Operational Overview of the First Offshore Production Test of Methane Hydrates in the Eastern Nankai Trough, the Offshore Technology Conference. Houston, Texas, USA, OTC-25243-MS: 25243. <https://doi.org/10.4043/25243-MS>.
- Yamamoto, K., et al., 2019. The second offshore production of methane hydrate in the Nankai Trough and gas production behavior from a heterogeneous methane hydrate reservoir. *RSC Adv.* 9 (45), 25987–26013. <https://doi.org/10.1039/c9ra00755e>.
- Yang, L., et al., 2016. Synchrotron X-ray computed microtomography study on gas hydrate decomposition in a sedimentary matrix. *G-cubed* 17 (9), 3717–3732. <https://doi.org/10.1002/2016gc.006521>.
- Yang, L., et al., 2023. The locally varying thermodynamic driving force dominates the gas production efficiency from natural gas hydrate-bearing marine sediments. *Energy* 276, 127545. <https://doi.org/10.1016/j.energy.2023.127545>.
- Yang, L., et al., 2025. Promoted hydrate decomposition behavior assisted by enhancing heat exchange with the geothermal energy. *Chem. Eng. J.* 512, 162662. <https://doi.org/10.1016/j.cej.2025.162662>.
- Ye, H., et al., 2025a. How injecting CO₂ enhances marine natural gas hydrate exploitation: review and prospect. *Renew. Sustain. Energy Rev.* 222, 116011. <https://doi.org/10.1016/j.rser.2025.116011>.
- Ye, H., et al., 2025b. Co-production of gas hydrates, shallow gas, and deep gas in the Qiongdongnan Basin: a pathway to commercial production. *Appl. Energy* 384, 125482. <https://doi.org/10.1016/j.apenergy.2025.125482>.
- Zhang, Y., et al., 2025a. Integrated detection of micro-pore structures and macro-mechanical responses for hydrate-bearing sediments. *Adv. Geo-Energy Res.* 17 (3), 184–195. <https://doi.org/10.46690/ager.2025.09.02>.
- Zhang, Y., et al., 2024. The pore-structure characteristics of foraminiferal shells and their relations with natural gas hydrate formation in the marine sediments. *Gas Sci. Eng.* 124, 205257. <https://doi.org/10.1016/j.jgsce.2024.205257>.
- Zhang, Y., et al., 2025b. Permeability prediction in hydrate-bearing sediments via pore network modeling. *Adv. Geo-Energy Res.* 16 (2), 158–170. <https://doi.org/10.46690/ager.2025.05.07>.
- Zhang, Z., et al., 2025c. Comparative analysis of three heating methods for natural gas hydrate production: electric heating, steam injection, and hot water injection. *Appl. Therm. Eng.* 269, 126131. <https://doi.org/10.1016/j.applthermaleng.2025.126131>.
- Zhao, E., et al., 2022a. Energy recovery behavior of low-frequency electric heating assisted depressurization in class 1 hydrate deposits. *Fuel* 309, 122185. <https://doi.org/10.1016/j.fuel.2021.122185>.
- Zhao, J., et al., 2022b. Gas production enhancement effect of underlying gas on methane hydrates in marine sediments by depressurization. *Fuel* 310, 122415. <https://doi.org/10.1016/j.fuel.2021.122415>.
- Zhao, Q., et al., 2025a. Dynamic competitive co-production behaviors between natural gas hydrate and higher-pressure shallow gas under wellbore interference: an experimental study. *Appl. Energy* 384, 125474. <https://doi.org/10.1016/j.apenergy.2025.125474>.
- Zhao, Y., et al., 2025b. Mechanical properties of gas hydrate-bearing sediments: research progress, challenges and perspectives. *Earth Sci. Rev.* 262, 105058. <https://doi.org/10.1016/j.earscirev.2025.105058>.
- Zhou, Y., et al., 2026. Temperature-dependent deformation of methane hydrate within phase boundary. *J. Mater. Res. Technol.* 40, 3831–3839. <https://doi.org/10.1016/j.jmrt.2026.01.084>.