Advances in
Geo-Energy Research

Vol. 21, No. 1, p. 4-8, 2026

Perspective

Natural gas hydrate exploitation with reservoir stimulation technology: Status and perspectives

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Keywords:
Natural gas hydrate
stimulation techniques
numerical modelling
experiment methods
artificial intelligence

Cited as:
Dong, L., Zhang, Y., Zhang, Y. Natural gas hydrate exploitation with reservoir stimulation technology: Status and perspectives. Advances in Geo-Energy Research, 2026, 21(1): 4-8.
https://doi.org/10.46690/ager.2026.07.02

Abstract:
Current exploitation of natural gas hydrate exhibits issues of low productivity, limited gas recovery rate, as well as unsatisfied input-output ratio, which is unfavorable for efficient production and further commercial development realization. Reservoir stimulation techniques applied in hydrate production still face challenges at both theoretical and technical levels. This paper systematically reviews representative reservoir stimulation technologies and their applications to evaluate current progress and future opportunities. Numerical simulations and laboratory investigations are comprehensively reviewed to summarize recent advances, identify existing limitations, and evaluate the potential application prospects of various stimulation techniques. On this basis, challenges and perspectives are discussed to point out potential approaches and development trends. It is recommended to establish a system of complex structure wells assisted with advanced stimulation techniques for higher productivity and target output ratio. This work provides a deeper understanding of control mechanisms underlying hydrate reservoir stimulation and facilitates the further commercial development of natural gas hydrate resources.

1. Introduction

Natural gas hydrate, as an alternative energy source, has strategic significance for energy shortage, environmental pollution, and climate change (Gajanan et al., 2024). As natural gas hydrate exploitation enters the stage of commercial development, higher productivity and improved economic efficiency are required, which may maximize expected huge prospects and achieve energy support in the future. Currently, single-well productivity of hydrate reservoirs remains significantly below the level required for commercial exploitation, proving the critical importance of multi-well systems and reservoir stimulation technologies in enhancing gas production performance (Wang et al., 2023b). These approaches can enhance hydrate productivity basically through enlarging drainage area, favoring dissociation efficiency, and strengthening seepage (Dong et al., 2024). Potential stimulation techniques have demonstrated significant enhancement effects in theoretical studies and have also been partially applied in field engineering practice. However, the underlying principles and controlling mechanisms remain insufficiently understood due to the lack of systematic investigations, which limits continuous improvement in production performance and hinders the anticipated commercial development of natural gas hydrate resources.

In this paper, hydrate reservoir stimulation technologies are systematically reviewed with a focus on fundamental mechanisms, productivity enhancement, as well as technical bottlenecks. Besides, progress in laboratory experiments and numerical modelling is clarified and compared to better bridge the gap between theoretical research and engineering practice. On this basis, challenges and perspectives are discussed to

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Received April 28, 2026; revised May 17, 2026; accepted May 26, 2026; available online May 27, 2026.

explore potential approaches for solving current issues. This work presents a reference for further development of advanced stimulation technologies and facilitates the commercial exploitation of natural gas hydrates.

2. Hydrate reservoir stimulation technology

To address the challenges associated with low-permeability and environmentally sensitive hydrate reservoirs, various stimulation technologies have been developed to enhance hydrate dissociation and improve production performance while ensuring geo-mechanical stability. Main stimulation technologies present significant differences in productivity improvement as well as application scope.

(1) Hydraulic fracturing technology. Hydraulic fracturing accelerates hydrate dissociation by creating high-conductivity artificial networks and strengthening fluid flow. Occurrence of gas hydrates enhances sediment cohesion and friction, often facilitating a transition from plastic to brittle failure, which improves reservoir fracturability (Feng et al., 2019). Besides, fracture propagation is a complex thermal-hydraulic-mechanical-damage coupled process, wherein fracturing fluid disrupts phase equilibrium to trigger hydrate dissociation. It usually weakens particle cementation, further governing the directional growth of fractures along with the minimum principal stress.

(2) Radial well technology. Radial well technology utilizes hydraulic jetting to create multiple small-radius branch wellbores, significantly expanding the drainage area with lower costs compared to conventional horizontal wells. This approach is highly adaptable to shallow reservoirs, though it introduces risks of stress concentration and sand production in the exploration process (An et al., 2025). Combining radial wells and hydraulic fracturing can generate continuous plastic zones, ensuring stable and directional fracture propagation to enhance synergistic production between branches.

(3) Solid-state fluidization. The solid-state fluidized mining method involves fracturing the hydrate-bearing reservoir and transporting the resulting slurry to a sea-level platform. This approach allows hydrates to decompose stably during transportation, mitigating the risks of sudden, massive in-situ dissociation. Furthermore, backfilling residual sediments promotes environmental restoration, a concept successfully validated during field tests in the South China Sea in 2017 (Li et al., 2018).

(4) Through-throat reaming. Through-throat reaming utilizes specialized working fluids, often acid-based systems, to address near-wellbore formation damage and screen blockages. By enlarging pore throat radii and enhancing local permeability, this technology mitigates production decline. Advanced simulation models now allow for the precise optimization of reaming parameters based on damage coefficients, enabling tailored stimulation treatments for complex marine clayey silts.

(5) Split grouting. Split grouting involves injecting high-pressure slurry to create a structural mesh skeleton within the reservoir. It simultaneously enhances geo-mechanical stability and gas-water seepage capacity. The goal is to develop a dual-enhancement system where a stable, porous skeleton maintains high inflow capacity even as the hydrate dissociation process weakens the original sediment matrix.

(6) Cover modifications. For unconfined reservoirs lacking impermeable caps, constructing an artificial CO_2 hydrate cover provides a novel solution. By injecting CO_2 into the overlying layers, formed hydrate cap in target regions blocks seawater intrusion, prevents gas leakage, and further inhibits sand production (Sun et al., 2019). This synergistic approach not only improves decompression efficiency and gas mobility, but also achieves safe subsea CO_2 sequestration while maintaining long-term geological stability.

3. Main research approaches

3.1 Numerical modelling

Productivity assessment and geological risk prediction are indispensable for the development of hydrate reservoirs. Numerical modelling of hydrate production with complex structure wells is primarily established by multi-field coupling theory, which provides the fundamental framework for accurately describing the physical processes occurring during production. Generally, hydrate exploitation is a typical thermal-hydrodynamic-mechanical-chemical coupled process involving heat and mass transfer, multiphase flow, solid deformation, as well as hydrate dissociation (Yu et al., 2026). Furthermore, there is an essential step to solve these mathematical models in a unified framework with proper simulators, as depicted in Fig. 1(a). Existing simulators can mainly be classified into two categories: commercial software linking to hydrate simulators and fully coupled simulators (Wan et al., 2022). The latter can realize two-way coupling interaction with high accuracy based on sufficient computation, which is a proper approach for analyzing complex mechanisms governing hydrate production processes.

Investigations of production and deformation behaviors of hydrate reservoirs concentrate on produced gas volume, pore pressure, hydrate saturation, stress and strain distributions, as well as flow characteristics, which has tight association to efficient and safe development. Simulators perform well for analyzing hydrate development process with complex structure wells and corresponding engineering issues, which contains sand production, wellbore stability, landslides, subsidence and other risks(Yan et al., 2020). Also, CO_2 replacement processes have been incorporated into numerical models to ensure accurate descriptions of gas extraction and CO_2 storage (Gu et al., 2025). Nevertheless, existing simulation approaches still faces challenges in computational efficiency and model applicability, hindering accurate characterization of complex field conditions.

Radial well technology, utilizing hydraulic jetting to create small-radius branch wellbores, significantly expands the drainage area while reducing drilling costs and operational risks compared to conventional horizontal wells. Production enhancement is strongly dependent on the number and cumulative length of radial branches, making this technology particularly suitable for shallow hydrate reservoirs. Meanwhile, pressure drawdown and well positioning determine

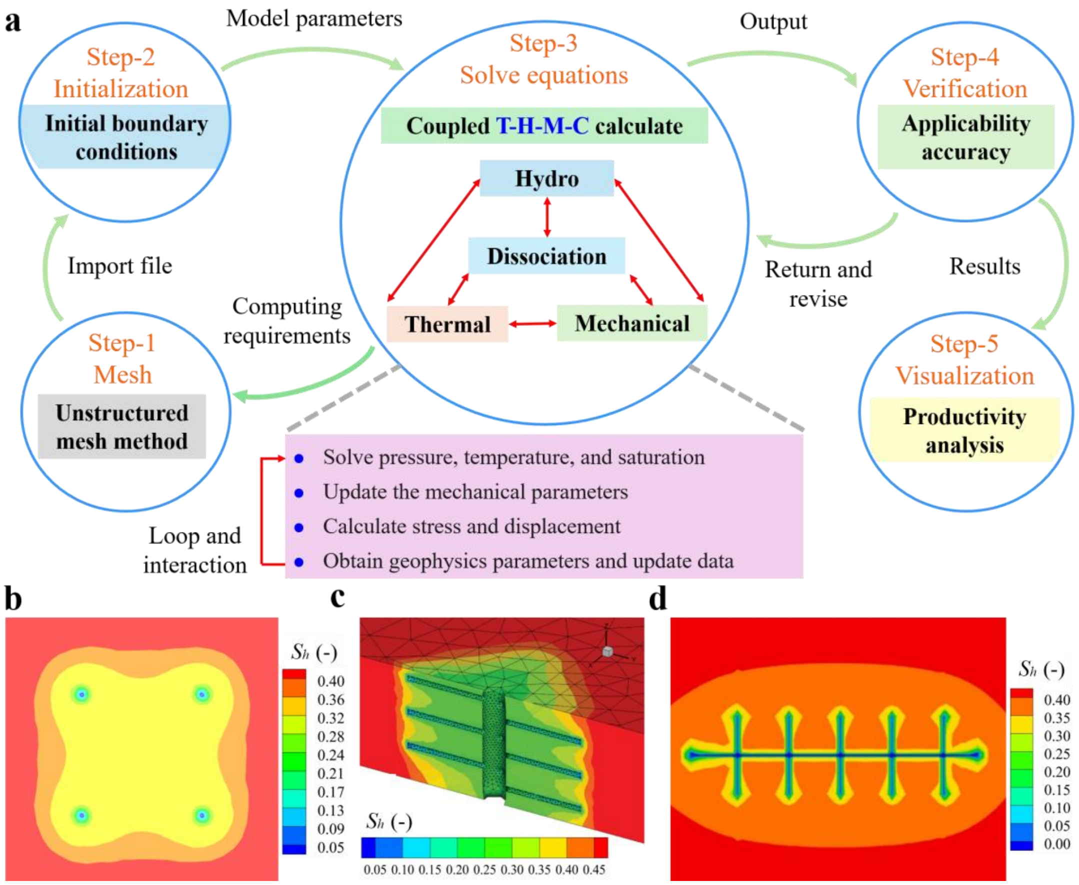

Fig. 1. Numerical modelling for natural gas hydrate development. (a) Typical modelling process and key steps summarized from (Dong et al., 2023). (b) Numerical simulation of hydrate production with multi-well system. (c) Application of numerical simulations for analyzing hydrate saturation distribution during hydrate production with multi-branch wells. (d) Numerical modelling for hydrate production assisted with hydraulic fracturing stimulation (Guo et al., 2024).

reservoir subsidence and operational safety largely due to depressurization-induced localized stress concentrations. In addition, optimizing multi-branch layouts promotes maximizing gas recovery and economic feasibility, as displayed in Fig. 1(c). Radial well designs must be combined with thermal-depressurization strategies to overcome multi-well interference and sustain output in low-permeability reservoirs. Therefore, further investigations are required to optimize branch-well configurations and enhance the synergy between well architecture and reservoir stimulation methods.

Hydraulic fracturing is essential for creating fluid pathways that enhance flow and promote hydrate dissociation in low permeability reservoirs (as shown in Fig. 1(d)), wherein numerical simulations are crucial for optimizing operational parameters. For hydrate reservoirs with a free gas layer, hydrate reformation at the phase interface can limit overall recovery while fracturing accelerates early-stage dissociation. However, coupling horizontal fracture networks with boundary sealing can still significantly enhance long-term production. For hydrate reservoirs with existing nonpermeable layers, the combined application of hydraulic fracturing, depressurization, and thermal stimulation has proven to be highly effective, although such systems are often associated with relatively low baseline gas production rates. Moreover, optimization of fracture geometry and thermal energy input can maximize productivity, improve energy efficiency, and significantly reduce the required number of production wells.

3.2 Laboratory experiments

Laboratory experiments serve as widely applied approaches for characterizing gas recovery processes and influencing factors, providing fundamental datasets for productivity evaluation and for elucidating underlying mechanisms. Current studies concentrate on hydrate extraction processes with complex structures and multiple wells, wherein gas recovery rate, produced gas volume, and formation responses are estimated quantitatively. However, single-well systems often fail to achieve satisfactory productivity, emphasizing the importance of multi-well configurations. Another feature is that there is an increasing trend in simulator volumes and well numbers, which is intended to simulate actual conditions of fields for higher output and efficiency. Besides, development of well pattern undergoes single vertical/horizontal well to complex structure well and then to well groups that represents the increasing output demand and continues technique advancement. Overall, laboratory experiments correspond to target productivity enhancement and actual requirements of field trial production.

Laboratory simulations have fundamentally shifted from basic kinetic modelling to evaluating macroscopic extraction strategies applying large-scale reactors with designed complex multi-well architectures. While advanced configurations of radial and multi-branch wells demonstrate significantly enhanced productivity, they concurrently expose critical engineering bottlenecks, primarily including complex multiphase flow dynamics, and geo-mechanical instability. The most pressing challenge lies in the scale-up process. Inherent constraints, including reactor volume limits, boundary effects, and idealized heat transfer conditions, make it difficult to satisfy the complex similarity criteria required for field-scale translation. Furthermore, aggressive production strategies frequently trigger unintended consequences such as secondary hydrate formation and severe sand production. Therefore, future experimental paradigms must bridge the gap between pore-scale analyses and macroscopic reservoir behavior to provide robust theoretical support for commercial deployment.

4. Challenges and perspectives

(1) CO_2-assisted methane extraction and field sequestration applications. The CH_4-CO_2 replacement method, often combined with depressurization, offers a compelling dual-benefit strategy for simultaneous gas extraction and carbon sequestration while mitigating sediment subsidence (Koh et al., 2016). Recent advancements integrate hybrid thermal-chemical stimulation with complex well architectures, such as radial horizontal or multilateral wells with cyclic CO_2 injection (Wang et al., 2023a). Optimizing this process requires a multiscale modeling approach to dynamically adjust critical parameters, such as injection temperature, soaking time, and pressure, which can maximize methane recovery, prevent rapid gas breakthrough, and ensure long-term reservoir stability. Besides, theoretical feasibility of this substitution mechanism has been successfully validated through the progression of deep-sea experiments and terrestrial field trials, i.e., foundational ROV studies in Monterey Bay (Brewer et al., 2014). These pioneering tests unequivocally confirmed the viability of in-situ CH_4-CO_2 replacement, underscoring the critical need for robust sand control, well spacing optimization, and flow assurance to achieve commercial-scale application.

(2) Advanced multi-scale and multi-field coupled modelling. As the development of natural gas hydrates transitions toward commercialization, the fidelity of predictive numerical models becomes paramount. Current simulations frequently oversimplify the inherent heterogeneity of geological formations, which requires high-precision, multi-field coupled models capable of capturing complex dynamic phenomena (e.g., fluid fingering) under realistic geological conditions. Furthermore, existing thermodynamic models often rely on bulk phase equilibrium data, neglecting the profound influence of the microscopic pore environments typical of marine sediments. It is imperative that future experimental studies quantify these pore-scale confinement effects to refine thermodynamic boundary curves, especially efficiency balance point between methane extraction and CO_2 sequestration. To overcome the persistent scaling barriers between small-scale laboratory observations and reservoir-scale field applications, a robust mathematical framework for "micro-to-macro" parameter upscaling must be established.

(3) Applying artificial intelligence for efficient evaluation of hydrate production. Current machine learning methods are widely applied to hydrate exploitation with intelligent prediction and pattern recognition based on experiment and simulation data, concentrating on thermodynamic parameter determination, reservoir assessment, and CO_2 capture related to hydrate (Gjelsvik et al., 2023; Hosseini and Leonenko, 2023). These approaches play a critical role and exhibit immense potential for hydrate development. On the one hand, machine learning can improve accuracy and efficiency of predicted models that further promote productivity evaluation and development strategy design. On the other hand, introducing explainable learning in hydrate dissociation and gas extraction may promote traditional prediction transferring into intelligent analysis, which helps extend the regularity identification to mechanism interpretation. Therefore, there is an increasing demand for establishing intelligent decision systems integrating field data, numerical modelling, and AI-driven optimization, which can support commercial hydrate development in complex conditions.

5. Conclusions

Natural gas hydrate development faces challenges of low productivity and unsatisfied output ratio, which limits efficient production and commercial development realization. Several hydrate reservoir stimulation technologies have been developed to enhance productivity as well as recovery efficiency, wherein hydraulic fracturing and radial well techniques exhibit strong potential for field applications. It is feasible to establish a complex structure well system assisted with stimulation techniques to achieve satisfied productivity and promote commercial exploration.

Numerical modelling and laboratory experiments provide sufficient data and key factor investigations for accurate descriptions of hydrate recovery under numerous conditions, which forms a foundation for revealing control mechanisms as well as designing production strategies. On this basis, future development requires multi-field coupling models with higher accuracy and practicality for hydrate extraction processes with stimulation technologies.

Several essential issues emerge with increasing demand for efficient hydrate development, especially CO_2 related gas recovery, carbon sequestration, proper multi-scale models, and artificial intelligence applications. Current challenges need to be addressed accurately by introducing new approaches and applying detection technologies. Solving these problems can expand understanding of control mechanisms and promote the application of simulation techniques during hydrate production, which also indicates the future direction of commercial development.

Acknowledgements

This research was supported by National Key Research and Development Program of China (No. 2023YFC2811001), National Natural Science Foundation of China (Nos. 42506223, 52422402 and 42576245), and Taishan Scholar Program. These financial supports are gratefully acknowledged.

Conflicts of interest

The authors declare no competing interest.

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