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Research progress and scientific challenges in the depressurization exploitation mechanism of clayey-silt natural gas hydrates in the northern South China Sea

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Abstract:
Natural gas hydrate reservoirs in the northern South China Sea primarily comprise clayey silt, making exploitation more challenging relative to sandy reservoirs in other countries and regions. This paper provides an overview of the latest research developments in the exploitation mechanism covering the past five years, focusing on hydrate phase transition, multiphase flow in the decomposition zone, the seepage regulation of reservoir stimulation zone, and production capacity simulation, all of which are relevant to the previously conducted two rounds of hydrate trial production in offshore areas of China. The results indicate that the phase transition of clayey-silt hydrate remains in a dynamic equilibrium, with the decomposition efficiency mainly controlled by the coupling of heat and flow and high heat consumption during decomposition. The decomposition zone exhibits strong hydrophilicity, easy adsorption, and sudden permeability changes. A temperature drop is present that is concentrated near the wellbore, and once a water lock has formed, the gas-phase flow capacity significantly decreases, leading to potential secondary hydrate formation. To enhance permeability and increase production, it is imperative to implement reservoir and temperature field reconstruction based on initial formation alterations, which will further optimize and improve the transport capacity of the reservoir.

1. Introduction

Natural gas hydrates are predominantly found in solid form within the seabed sediments of continental shelves. Preliminary estimations have indicated that global hydrate resources amount to approximately 20 trillion tons of oil equivalent (Sloan and Koh, 2007; Zou et al., 2013). Thus, promoting the large-scale commercial development of hydrates holds significant importance for ensuring national energy security and advancing low-carbon, sustainable development.

According to the "2022 Research Frontiers" released by the Institutes of Science and Development, Chinese Academy of Sciences, the field of reservoir characteristics and exploitation technology of natural gas hydrates is ranked among the top eight forefront issues in Earth Science (Pan et al., 2023). The efficient development and utilization of natural gas hydrates can be achieved in five stages: theoretical research and simulation experiments, exploratory trial production, experimental trial production, productive trial production, and commercial exploitation. Since 2002, some countries such as the United States, Canada, and Japan have primarily employed depressurization as the principal means of exploiting hydrate from

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sandy reservoirs and conducted six production trials (Moridis et al., 2005; Numasawa, 2008; Schoderbek et al., 2013; Terao et al., 2014; Oyama and Masutani, 2017; Wu et al., 2017). These were all found to face three common challenges: low gas production per well, short stable production periods, and difficulties in pressure control. Consequently, the anticipated objectives were not achieved, and the efficient and safe exploitation of natural gas hydrate has remained a significant global technological challenge.

Offshore natural gas hydrate resources in China hold tremendous potential, which typically occur within soft and unconsolidated clayey-silt sediment on the seabed, presenting greater exploitation challenges compared to sandy reservoirs. China launched exploratory and experimental trial production in the Shenhu area of the South China Sea in 2017 and 2020, and these efforts have accelerated the progress towards industrialization (Ye et al., 2020).

Overall, both domestic and international scholars have obtained a series of innovative results in the fields of natural gas hydrate reservoir formation and trial production engineering (Gao, 2020; Ning et al., 2020; Qin et al., 2020a ; Su et al., 2020; Zhang et al., 2020). In terms of exploitation theory, numerous effective studies have been conducted using experiments and numerical simulations (Cai et al., 2020b; Li et al., 2020; Wei et al., 2020; Lu et al., 2021d; Wu et al., 2021). However, research on clayey-silt natural gas hydrates in the northern South China Sea is still in its preliminary stage, requiring a focus on the reservoir actualities and the continued exploration of exploitation mechanisms.

The analysis of the entire trial exploitation process of clayey-silt hydrate in the northern South China Sea reveals the following observations. Hydrate phase transition persists throughout, with depressurization decomposition leading to the release of gas and water from the decomposition front through the clayey-silt containing decomposition zone. Upon entering the stimulation zone, these converge towards the wellbore and are extracted. During the above process, complex physical and chemical transformations of the solid, fluid and gas phases occur. The gas flow capacity in the decomposition zone is relatively weak, leading to a continuous decrease in permeability. A consistently high flow capacity in the stimulation zone is challenging to maintain for an extended period. The "reservoir-wellbore" complex trial exploitation system formed by two distinct physical domains experiences sustained cooling, resulting in a temperature funnel, which may lead to the formation of secondary hydrates or ice and affect production. Additionally, the lack of mature gas reservoir engineering methods and corresponding production capacity control techniques negatively impacts pre-trial production predictions, in-trial work system adjustments, and post-trial historical fitting at the same time, and the exploitation patterns for this type of hydrate remain unresolved.

Fig. 1 demonstrates the generally used depressurization method for the exploitation of natural gas hydrates in the South China Sea. This method is independent of well type. In the process, pressure in the reservoir around the wellbore is reduced below the stable pressure of the hydrates, causing them to undergo decomposition into natural gas and water. These products then flow to the wellbore where a separation device is used to separate the gas from the water before exploitation, ensuring the production of natural gas at the wellhead. Research efforts targeting the "undecomposed zone" of gas hydrates should focus on the molecular dynamics and gas hydrate phase equilibrium of hydrates in the South China Sea. In the "decomposition front zone," emphasis should be placed on the interaction between hydrate occurrence modes and reservoir physical properties, as well as the phase transition of hydrates and reservoir structure evolution. In the "decomposition zone," research should revolve around the characterization of porous medium mineral composition and micro-nano pore structure, methane gas adsorption and diffusion during decomposition, changes in the reservoir structure and permeability with production pressure differences, the characteristics of relative permeability for gas and water phases, reservoir modification, sand control, and seepage regulation, as well as the mechanism of "reservoir-wellbore" temperature field modification and restoration. Based on the results on these parameters and utilizing the spatiotemporal evolution laws of multi-field coupled processes in gas hydrate exploitation and production simulation, the depressurization strategy and plan for trial production as well as the supporting of geological and engineering project design were ultimately achieved by reconstructing the three-dimensional geological characteristics of gas hydrate reservoirs and numerical models for gas hydrate exploitation.

Accordingly, this review focuses on four key issues related to clayey-silt hydrates: phase transition, multiphase flow in the decomposition zone, transport capacity optimization in the stimulation zone, and production capacity regulation and control. The paper provides an overview of the latest research achievements made by academics in the field of natural gas hydrate exploitation mechanisms in the South China Sea in recent years. The content covers various aspects, including molecular simulation, phase equilibrium, occurrence patterns, reservoir property evolution, pore structure characterization in the decomposition zone, methane adsorption, the relationship between reservoir structure and permeability changes, gas-water relative permeability, water lock characteristics, secondary hydrate generation around the wellbore, "reservoir-wellbore" temperature field stimulation, reservoir transport capacity optimization, production capacity simulation, and depressurization strategies. The paper systematically elaborates on three main aspects of this type of hydrate: how it decomposes in the reservoir, how it flows effectively within the reservoir post-decomposition, and how optimal and efficient exploitation is supported. The future development directions are also discussed, providing a theoretical foundation for the efficient development and utilization of natural gas hydrate resources.

2. Research progress

2.1 Natural gas hydrate phase transition

Natural gas hydrate phase transition refers to the phase transformation among hydrate, dissociated gas and water, forming the basis for gas production within the reservoir.

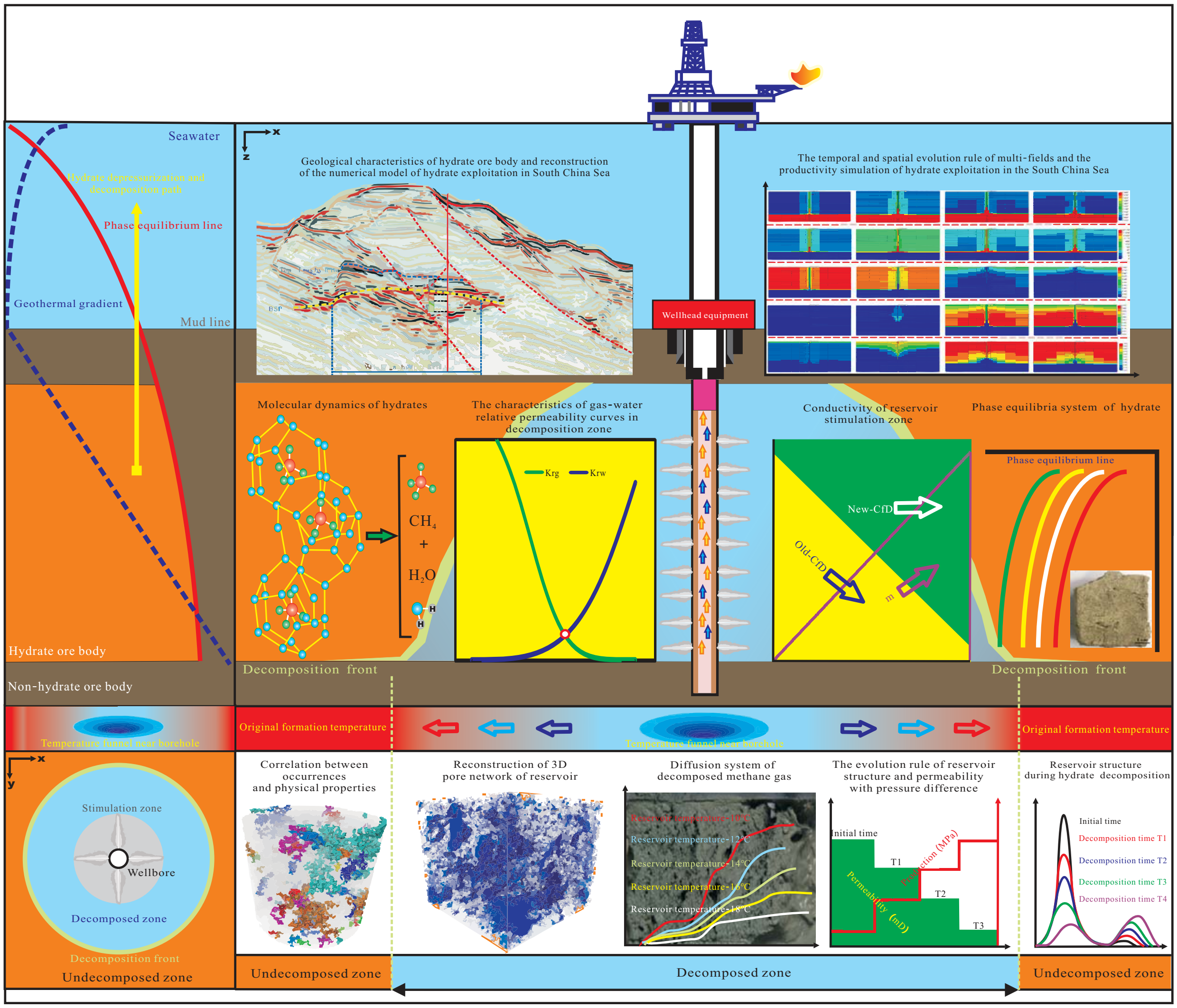

Fig. 1. Schematic diagram of the depressurization exploitation seepage mechanism in clayey-silt natural gas hydrate

Phase transition is influenced by multiple parameters and mechanisms, with substantial debates among scholars regarding the relevant mechanisms and effects. This is especially true for clayey-silt hydrates for which a unified understanding has not yet been established, making it a focal point of current research and a key direction for future development (Sun et al., 2021a). It is essential to consider factors such as solid surface crystallinity and hydrophilicity in clayey-silt reservoirs to establish solid molecular models of hydrate based on actual mineral compositions and pore structures (Qi et al., 2021). The equilibrium curve of clayey-silt hydrates compared to the pure water-methane system notably shifts to the left, indicating lower decomposition temperatures, higher decomposition enthalpy, and a propensity for secondary hydrate formation. Improved equilibrium prediction models can accurately predict the critical temperature and pressure points for hydrate decomposition in the South China Sea (Geng et al., 2021). By utilizing depressurization methods, it has been found that hydrate phase transition is consistently in a dynamic equilibrium with formation and decomposition occurring simultaneously. Sheet-like and clustered hydrates within pore spaces predominantly decompose, leading to a significant enhancement of reservoir transport capacity, and ultimately transform into isolated hydrates that are difficult to degrade (Bian et al., 2022). Meanwhile, biogenic fossils, particularly Foraminifera, provide potential space for hydrate aggregation. The lagging effect of hydrate phase transition in clay-rich sediments is more pronounced than that in quartz-rich sediments, resulting in dispersed hydrates that fill pores and affect the efficiency of continuous gas release during depressurization (Bian et al., 2023). Various permeability change models have been constructed under different assumptions but they have difficulty in accurately characterizing the dynamic relationship between clayey-silt hydrate saturation and reservoir permeability after phase transition (Zhang et al., 2022).

2.2 Multiphase flow in the decomposition zone

Multiphase flow in the decomposition zone of natural gas hydrates, which is essential for gas production, refers to the flow of multiphase substances, including gas, water and isolated-dispersed hydrates, within the reservoir after hydrate decomposition. To date, research on the flow patterns within the decomposition zone of clayey-silt hydrate, from the decomposition front to the production wellbore area, has been relatively limited. This area is a key point for both current and future research breakthroughs. Clayey-silt reservoirs exhibit a relatively high fractal dimension, with a more complex distribution of pore space compared to conventional sandstones (Bian et al., 2020). The dominant pore types here are clay pores and biogenic fossil pores, with a wide distribution of average pore radius and median pore radius often below 1.5 μm. Microscale pores are well developed, rich in hydrophilic clay minerals, and mainly include illite (Lei et al., 2022; Lu et al., 2022b). The pressure gradient of 3 MPa/m is a critical point at which the pore structure and permeability of such reservoirs undergo rapid changes (Lu et al., 2019). Beyond this point, larger pores and throats available for fluid flow become less abundant while the number of smaller ones increases, resulting in a reduction in average/maximum pore and throat radius, ultimately leading to decreased and irreversible permeability (Cai et al., 2020a). When the reservoir temperature is lower than that of shale, the adsorption capacity is similar to illite and much lower than montmorillonite. The impact of water saturation on methane adsorption varies across different pressure ranges (Qi et al., 2022). The relative permeability curve for the two phases of clayey silt shows a rightward and lower-shifted position of the equal permeability points. The co-permeability zone is narrow and the maximum relative gas permeability is less than 0.1 (Lu et al., 2021c). Higher water saturation leads to the earlier formation of a water lock, making it extremely challenging for gas to flow through the water film in narrow channels and drastically reducing the gas flow capability (Zheng et al., 2023). Under the same conditions of decomposition range, the throttling expansion effect has a significant impact. Within a 5-meter radius of the wellbore, hydrate is highly susceptible to reformation. With a larger pressure difference, the secondary hydrate formation zone tends to concentrate closer to the wellbore wall, potentially leading to ice blockages and increasing the flow resistance in the wellbore. Under the same pressure differential conditions, the "temperature funnel" has its steepest slope near the wellbore wall. As the decomposition zone expands, the rate of temperature decrease slows down, making the formation of secondary hydrates less likely (Sun et al., 2018; Ma et al., 2022). Effective reservoir stimulation is thus essential for reducing the flow resistance of decomposed gas near the wellbore, enabling successful production.

2.3 Optimization and control of reservoir transport capacity

Reservoir transport capacity is a critical factor in determining the long-term and efficient exploitation of clayey-silt hydrates. The existing methods for optimizing and controlling fluid flow capacity are relatively limited and lack a systematic approach for efficient development. At the same time, mechanistic studies on factors such as increasing permeability and production, repetitive stimulation, and temperature field stimulation, which impact the exploitation efficiency, are still in their early stages. Clayey-silt hydrates can form single-wing fractures, but conventional proppants like quartz sand tend to close these fractures. There are numerous microfractures and a small number of pores around the wellbore, with lower hydrate saturation leading to easier pore formation (Sun et al., 2021b). Similarly, the decomposition zone of clayey silt exhibits significant artificial fracturing capacity. Higher confining pressure and plastic deformation will result in the formation of horizontal fractures and small fracture zones, leading to the creation of numerous microfractures around the wellbore (Lu et al., 2021a). Optimizing the parameters such as artificial fracture permeability, half-length and width can significantly reduce the fluid flow resistance at the bottom of the wellbore decomposition zone, promoting pressure diffusion and hydrate decomposition (Xu et al., 2023). Meanwhile, higher artificial fracture conductivity compared to natural fractures is more favorable for increasing daily gas production. However, this will significantly increase the temperature drop within the fracture, making the formation of secondary hydrates more likely (Cui et al., 2023). Similar to fracture-type hydrates, if secondary hydrates within the fracture undergo decomposition, their overall mechanical strength will decrease by more than 30%, or in some cases exceeding 60%. This degradation is significant, with a reduction in the internal friction angle being the primary factor causing noticeable differences in strength (Lu et al., 2022a). A series of independently developed enhancements for clayey-silt reservoirs, including reinforced frameworks and amorphous porous materials, can effectively reduce the risk of channels formed by conventional quartz and lightweight ceramic bridging being extensively blocked by clayey silt. This enhances the flow capacity in the reservoir stimulation zone, providing support for the subsequent dynamic regulation of fluid flow capacity in such reservoirs. Simultaneously, based on horizontal well reservoir stimulation techniques, the innovative calcium oxide-based in-situ reheating and pressure reduction filling method was proposed. Under optimized parameters such as stimulation zone permeability and calcium oxide injection volume, this method can effectively supplement the heat generated during hydrate decomposition, leading to a significant increase in cumulative production (Xu et al., 2021a, 2021b).

2.4 Production simulation and control

Production simulation is a crucial approach for understanding the dynamics of gas hydrate exploitation and identifying sensitive exploitation factors; it serves as a vital foundation for devising control strategies. Simulators are essential tools for conducting production capacity simulations. At present, the commonly utilized simulators include TOUGH+Hydrate from the United States and CMG from Canada. In accordance with the characteristics of gas hydrate deposits in the South China Sea, numerical simulation studies were performed using a series of self-developed numerical simulators, with Hydrate Smart (V1.0) (Qin et al., 2019) as the core and supplementary tools such as Hydrate Captain (V1.0) (Lu et al., 2020, 2021b; IGGCAS, 2021; Qin et al., 2021; CUGB, 2022).

Based on the phase equilibrium distance method reflecting the comprehensive driving force of hydrate decomposition, it has been confirmed that higher initial reservoir temperatures lead to stronger continuity in exploitation. Under conditions of no external heat supply, higher gas production rates can cause increased pore pressure, coupled with the consumption of decomposition heat, resulting in reduced reservoir temperature. This in turn leads to a slowdown and eventual cessation of the decomposition rate and may even result in the formation of secondary hydrates (Li et al., 2022). Heat consumption during hydrate decomposition consists of three components: geothermal supply, sensible heat, and latent heat. Three distinct decomposition control modes can be identified: (1) In the flow mode, the decomposition rate is mainly influenced by the reservoir transport resistance. (2) In the heat transfer mode, the decomposition rate is significantly affected by the heat supply. (3) In the heat-flow coupling mode, both an increase in permeability and heat supply positively contribute to higher gas production. The clayey silt hydrate in the South China Sea tends to exhibit the third mode (Zhang et al., 2023). This type of hydrate reservoir exhibits an initiation pressure gradient. The larger the initiation pressure gradient, the smaller the radii of both the pressure funnel and temperature funnel; however, the depth of the temperature funnel shows a trend of initially increasing and then decreasing. This leads to a reduction in the extent of bottom water cone advancement and limits pressure transmission, thereby restraining the increase in production (Lu et al., 2022c). In the first round of offshore hydrate trial production of China, continuous depressurization was conducted through a vertical well for 60 days. The radius of hydrate decomposition in the reservoir was approximately 5 meters, with the volume of decomposed gas accounting for 85% of the cumulative gas production. If the trial production continues, the transmission of pressure drop funnels will be restricted, leading to the formation of a wide area of secondary hydrates at the location of hydrate decomposition front. This will result in a decrease in the rate of gas production due to decomposition (Qin et al., 2020a).

Comprehensive research on various aspects, including the phase transition, multiphase flow in the decomposition zone, optimization and control of reservoir transport capacity, and the production simulation of clayey-silt gas hydrate in the South China Sea, has yielded a depressurization strategy: gradually and gently reducing the bottomhole flowing pressure, preventing the formation of ice and secondary hydrates, maintaining effective reservoir transport capacity over the long term, and gradually increasing the production pressure differentials to expand production. This strategy has been successfully applied and validated during the implementation of the second round of trial production (Qin et al., 2022).

3. Conclusions

Natural gas hydrate resources in the northern South China Sea have immense exploration and development potential. The efficiency of gas production is influenced by various factors and mechanisms, involving aspects such as hydrate phase transition, multiphase flow in the decomposition zone, reservoir transport optimization, and production simulation. However, the mechanism of depressurization and gas production is complex and still not deeply understood. Existing research on the phase transition of mud-dominated sedimentary gas hydrates show that it remains in a dynamic equilibrium state. The efficiency of decomposition is primarily controlled by heat flow coupling, and heat is predominantly consumed during the decomposition process. The decomposition zone exhibits the characteristics of strong hydrophilicity, easy adsorption and abrupt changes in permeability. Temperature decline is concentrated near the wellbore, and once a "water lock" has formed, the gas phase flow capacity significantly decreases, making the formation of secondary hydrates more likely. Based on the initial reservoir stimulation, it is crucial to implement repeated stimulation and temperature field stimulation-restoration measures for the reservoir to further optimize and enhance the reservoir transport capacity, aiming to achieve enhanced permeability and production expansion. Future research in the field of natural gas hydrate reservoir phase transition and seepage mechanisms in the South China Sea should focus on the following aspects:

1) From the perspective of hydrate phase transition, it is necessary to further establish characterization methods for physical parameters under different hydrate occurrence modes based on continuous phase transition and construct mathematical models for their dynamic evolution, in order to provide a foundation for more accurate capacity control.
2) In terms of fluid flow mechanisms, it is essential to understand the dynamic variations in relative permeability and capillary pressure in hydrate-bearing phase transition reservoirs, clarify the main controlling factors of multiphase seepage, and establish a relative permeability model from core to field.
3) Regarding enhanced permeability and production expansion, it is urgent to conduct research on wellbore reservoir stimulation and support, the comprehensive skin effect under the influence of multiple parameters, and reservoir-wellbore temperature field stimulation and restoration. These efforts should aim to reveal the varying characteristics of reservoir transport capacity under different phase control regimes and evaluate the effectiveness of production enhancement.
4) For production capacity control, it is vital to conduct continuous iteration and updating of numerical computational models that couple the phase transition, seepage, and various complex effects in South China Sea hydrate to clarify the primary controlling factors limiting gas production volume. This will enable targeted adjustments to depressurization strategies.

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Conflict of interest

The authors declare no competing interest.

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