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Perspective

Mitigating risks in deep sea gas hydrate production: A new perspective on interpreting thermo-hydro-mechanical feedbacks

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Abstract:
Natural gas hydrate deposits in marine sediments represent a vast potential energy resource, yet their commercial extraction remains a complex scientific and engineering challenge due to the intricate thermo-hydro-mechanical-chemical coupling processes triggered during production. This perspective paper synthesizes recent progress and outlines persistent hurdles in understanding the coupled mechanical-seepage-thermal response inherent to gas hydrate exploitation, while introducing a novel theoretical and methodological framework that integrates cross-scale constitutive modeling, multiscale permeability upscaling, and nonlinear flow characterization to better interpret key feedback mechanisms. Looking forward, overcoming these barriers requires interdisciplinary approaches leveraging advanced sensing technologies, machine learning-assisted modeling, and novel upscaling methodologies. Furthermore, internationally collaborative long-term field trials with comprehensive monitoring are essential to validate next-generation simulators and develop adaptive management strategies.

1. Introduction

Natural gas hydrate is widely distributed in marine sediments and permafrost regions. It is considered a promising future energy resource due to its vast global reserves. The safe and efficient extraction of natural gas from hydrate-bearing sediments is a complex process involving multiphysics coupling, where the mechanical, seepage, and thermal properties of the reservoir play a critical and interconnected role.

The importance of understanding the thermo-hydro-mechanical coupling response during exploitation cannot be overstated. Mechanically, hydrate dissociation, which is an endothermic reaction, leads to a loss of cementation and a reduction in sediment stiffness and strength. This can compromise the stability of the reservoir and the overlying formation, potentially leading to wellbore collapse, sand production, or even large-scale submarine landslides. From a seepage perspective, the process is twofold: the dissociation of solid hydrate into gas and water increases the porosity and potentially the permeability of the formation, while the released gas and water must then flow through the sediment pores to the production well. This evolution of permeability is highly dynamic and spatially heterogeneous, governed by the dissociation front and sediment properties. Thermally, the dissociation process is highly endothermic, requiring a continuous supply of heat. The rate of dissociation is thus controlled by the heat transfer efficiency from the surrounding formation and/or from injected fluids. The cooling effect caused by dissociation can lead to the reformation of hydrate or ice, causing blockages and severely hindering gas and water flow.

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Therefore, the coupled mechanical-seepage-thermal responses form the fundamental core of any prediction model for gas production, determining both the efficiency of extraction and the geomechanical stability of the entire system.

This perspective paper aims to discuss the new progress in understanding this critical coupled system, synthesize the current state of knowledge, highlight persistent challenges, and propose potential pathways for future research to overcome these hurdles.

2. Methods for evaluating mechanical properties

2.1 Laboratory test

The high-pressure low-temperature hydrate triaxial apparatus is the most effective experimental equipment for studying the mechanical properties of hydrate-bearing sediments. Research has found that hydrate saturation can significantly enhance the strength and stiffness of sediments. This is primarily due to the cementation and filling effects of hydrates. As for the cementation effect, hydrates bind fine particles together, thereby increasing the overall strength; regarding the filling effect, hydrate particles fill the pores, increasing the overall density, which causes the sediments to exhibit mechanical properties similar to dense sand, showing greater shear dilation.

Additionally, high hydrate saturation tends to induce strain softening, which is more pronounced under low confining pressures. The reason is that the strength of hydrate particles is lower than that of the matrix sand particles, and an increase in hydrate particles leads to more particle breakage (Wu et al., 2021). Effective confining pressure is another significant factor influencing the mechanical properties of hydrate reservoirs, mainly because hydrate reservoirs are essentially a special type of hydrate-bearing soil. The fundamental characteristic of soil is pressure-dependent hardening, meaning strength and stiffness increase with higher confining pressure.

For hydrate-bearing sediments containing clay, the lubricating effect of clay can alter the interactions between particles, thereby affecting the mechanical properties of the reservoir. Studies have found that an increase in clay content can mitigate strain softening to some extent. Furthermore, historical stress is also an important factor influencing the mechanical behavior of the reservoir. A higher overconsolidation ratio results in greater strength and stiffness of the sediments, likely due to the more pronounced compaction effect on the sample under higher overconsolidation ratios. It is worth noting that under high confining pressure and high overconsolidation ratio, strain softening can easily occur due to particle breakage. Finally, it should be emphasized that there are coupling effects among the influences of the aforementioned different factors on the mechanical properties of hydrate-bearing sediments.

2.2 Constitutive model

Constitutive models serve as the foundation for numerical simulations and act as a critical bridge connecting fundamental experiments to field applications. Most existing constitutive models are developed for hydrate-bearing sediments of specific particle sizes, lacking a unified description across different particle size distributions. Yao et al. (2019) established the clay-sand unified hardening model, which provides direction for developing a unified constitutive model for hydrate-bearing sediments across varying particle sizes. The clay-sand unified hardening model introduces a key parameter, ph, which reflects the curvature of the normal consolidation line. Different values of ph correspond to different stress curvatures. By correlating ph with hydrate saturation-related quantities, a unified description of the compression characteristics of both clayey and sandy hydrate-bearing sediments can be achieved(Zhao et al., 2024). The cementation effect of hydrates enhances sediment strength and imparts certain tensile resistance, which can be modeled by introducing a cementation factor pc that causes isotropic expansion of the yield surface. The filling effect of hydrates can be represented by introducing a dilatancy factor pd, which leads to one-dimensional expansion of the yield surface along the p-axis. Finally, using a non-associated flow rule (as geotechnical materials do not follow an associated flow rule), and incorporating both pc and pd into the clay-sand unified hardening model, a unified constitutive model for hydrate-bearing sediments with cross-particle-size applicability can be established. If both pc and pd are zero, the yield function and plastic potential function completely reduce to those of the clay-sand unified hardening model.

The model demonstrates strong predictive capability for the mechanical behavior of hydrate-bearing sediments across different particle sizes. It can accurately predict strain softening, strain hardening, and plastic flow, as well as effectively capture the coupling effects of hydrate saturation and effective confining pressure, along with compression characteristics.

3. Flow characteristics

3.1 Upscaling model for permeability

During the extraction of natural gas hydrates, permeability plays a critical role in governing heat and mass transfer within the reservoir (Moridis et al., 2009; Waite et al., 2009). Consequently, numerous researchers have employed various methods to investigate the permeability of hydrate-bearing sediments. Nevertheless, due to the multi-scale nature of pore structures and their dynamic evolution resulting from hydrate formation and dissociation (Lei et al., 2020), the relationship between microscopic pore characteristics and permeability of hydrate-bearing sediments remains poorly understood.

A novel upscaling theoretical framework has been developed to accurately predict the absolute permeability and relative permeability of hydrate-bearing sediments while effectively capturing the influence of pore-scale structural variations induced by local heterogeneity. Firstly, three regions of interest and their corresponding representative elementary volumes in hydrate-free sediments are identified through digital rock techniques. Then, based on the morphological operation algorithm and the quartet structure generation set method, for each representative elementary volume (REV), hydrate-bearing sediment sub-samples with either pore-filling or grain-coating hydrate habits are generated. Subsequently, pore network modeling is performed on the sub-samples with different hydrate saturations to determine their flow properties. Finally, an equivalent hydrate-bearing sediments model is established, and its absolute permeability and gas-water relative permeability are predicted through single- and two-phase Darcy-scale flow simulations.

3.2 Nonlinear flow model for hydrate exploitation

It is reported that the fluid flow in the pore space of hydrate-bearing sediments in the South China Sea deviates from Darcy's law due to their narrow pore size and low permeability, exhibiting a threshold pressure gradient (Liu et al., 2020). Moreover, during hydrate exploitation, the thermal-hydraulic-mechanical-chemical coupling process causes a significant evolution of the threshold pressure gradient. This evolution affects fluid migration, impedes pressure diffusion, and affects hydrate extraction efficiency. However, the evolutionary behavior of the threshold pressure gradient in hydrate-bearing sediments remains poorly understood. Therefore, to enhance the efficient development of hydrate resources in the South China Sea, it is essential to develop a nonlinear flow model that incorporates the threshold pressure gradient to accurately simulate the flow behavior in these reservoirs.

A novel multiscale theoretical framework is developed to investigate the nonlinear flow characteristics of hydrate-bearing sediments in the South China Sea. Firstly, an analytical model for the threshold pressure gradient that accounts for effective stress is derived based on the microscopic pore structure of the sediments. Building upon this model, a one-dimensional nonlinear flow model incorporating thermal-hydraulic-mechanical-chemical couplings and sand production is established and solved. Finally, the influence of the threshold pressure gradient on gas and sand production behavior is analyzed. A case study based on the nonlinear model reveals that under a pressure drop from 3.5 to 1.5 MPa, cumulative gas production considering the threshold pressure gradient is approximately 57% higher than that predicted when the threshold gradient is neglected. However, as the threshold pressure gradient continues to increase, pressure propagation becomes significantly impeded, which suppresses hydrate dissociation and ultimately leads to a reduction in gas production.

4. Dissociation and heat absorption characteristics

4.1 Dissociation conditions

Natural gas hydrates in clayey silt sediments, which constitute a major portion of global reserves, exhibit dissociation behaviors distinct from those in bulk hydrate systems. Experimental investigations using step-heating and high-pressure differential scanning calorimetry have demonstrated that methane hydrate dissociation in clayey silts occurs at lower temperatures and higher pressures compared to pure water systems. This depression is attributed to reduced water activity resulting from capillary effects, salinity, and interactions with mineral surfaces.

The influence of sediment properties-such as grain size, mineral composition, and water content-on dissociation conditions has been systematically studied. Fine-grained quartz powders show moderate dissociation temperature depression ($\Delta T \approx$ 0.3-0.4 K), primarily due to capillary forces in small pores. In contrast, clay minerals such as montmorillonite induce significant depression (ΔT up to 8.5 K) because of their strong water-binding capacity within nanoscale interlayer spaces and through surface hydration (Chen et al., 20125). Sediments from the South China Sea, which contain complex mineral assemblages including clays, quartz, and organic matter, exhibit intermediate depression ($\Delta T \approx$ 2.3-3.8 K), underscoring the combined influence of pore structure and mineralogy.

A novel approach combining water activity measurement with the Chen-Guo thermodynamic model has been developed to accurately predict dissociation conditions (Zhao et al., 2021). By directly measuring water activity in sediment cores, this method eliminates the need for complex theoretical models of pore networks and mineral effects. Predictions correlate well with experimental data, with deviations within 0.68 K, offering a practical tool for assessing hydrate stability in natural sediments.

4.2 Heat absorption characteristics

The dissociation of gas hydrates is an endothermic process, and understanding its thermal characteristics is crucial for efficient extraction. Experimental measurements using differential scanning calorimetry reveal that hydrate dissociation in clayey silts occurs in multiple stages, reflecting the heterogeneous pore structure and variations in water-binding energy (Yu et al., 2024). The apparent heat of dissociation per unit volume of sediment is highly dependent on hydrate saturation, which is influenced by sediment type and water content. In quartz powders, hydrate saturation reaches 36.7-37.3%, with a heat absorption of 78.2 kJ/L. In montmorillonite and SCS sediments, lower saturations (13.9%-23.0% and 20.2%-23.0%, respectively) lead to reduced heat absorption (31.6 kJ/L and 34.6 kJ/L, respectively). This reduction results from the inhibition of hydrate formation by strongly bound water in clay-rich sediments (Chen et al., 20125). During the heating, hydrate reformation is frequently observed, caused by ice melting and enhanced gas access to previously isolated water. This phenomenon highlights the importance of thermal management during production to prevent hydrate re-stabilization.

Theoretical calculations based on reservoir conditions indicate that for low-hydrate-saturation reservoirs (<30%), in situ thermal energy may be sufficient for complete dissociation under high-pressure drawdown. For higher saturations, external energy input (e.g., thermal stimulation) is required to maintain economically viable production rates.

5. Challenges and perspectives

Despite significant advancements, the commercial exploitation of natural gas hydrate in marine environments remains fraught with substantial challenges, primarily stemming from the complex thermo-hydro-mechanical-chemical coupling processes. A primary obstacle is the critical scale gap between laboratory investigations and field-scale applications. Parameters like permeability, mechanical strength, and thermal properties measured in centimeter-scale cores are notoriously difficult to upscale accurately to represent heterogeneous reservoir conditions over hundreds of meters. This often leads to significant uncertainties in production forecasts and geomechanical risk assessments for field trials.

Furthermore, the spatial heterogeneity of natural marine sediments-including variations in hydrate saturation, sediment lithology, and formation permeability-is often inadequately represented in current numerical models. The common use of oversimplified, homogeneous models fails to capture the localized and often abrupt changes in dissociation fronts, fluid flow pathways, and stress redistribution, which are critical for predicting sand production and formation instability. The long-term coupled responses also present a major challenge. While short-term production tests have been successfully conducted, the enduring evolution of geomechanical stability over months or years of continuous production is poorly constrained. The potential for progressive subsidence, the long-term integrity of the wellbore, and the delayed response of the overburden require predictive models that are rigorously validated against long-term data, which is currently scarce. Another pressing issue is the transition from thermo-hydro-mechanical to thermo-hydro-mechanical-chemical coupling. Current models often lack a comprehensive integration of chemical processes, such as salt precipitation from pore water as fresh water is released during dissociation. This salt precipitation can clog pore throats, reducing permeability and hindering gas production, a feedback mechanism not yet fully accounted for in most simulators. Finally, there is an urgent need for real-time monitoring and adaptive management strategies. The ability to invert production data (e.g., pressures, temperatures, flow rates) in real-time to update reservoir models and adjust extraction parameters (e.g., bottom-hole pressure) is crucial for optimizing production and mitigating geohazards but remains a significant technological and computational hurdle.

Future perspectives for overcoming these challenges are emerging through interdisciplinary research. We propose the development and validation of a next-generation, fully coupled Thermo-Hydro-Mechanical-Chemical simulator with a focus on incorporating salt precipitation and dissolution dynamics. This simulator should integrate constitutive models capable of representing spatially heterogeneous sediments and include reactive transport modules to predict pore-scale chemical changes and their impact on permeability and strength. Another critical priority is the implementation of a real-time data assimilation and adaptive control framework for field trials. This framework would leverage distributed fiber-optic sensing data streams, combined with ensemble-based history matching techniques, to continuously update reservoir models and dynamically adjust production parameters (e.g., depressurization rates) to optimize recovery while minimizing risks like sand ingress and formation collapse. Fundamentally, closing the scale gap requires innovative laboratory experiments using larger-scale apparatuses and the development of new upscaling methodologies that can effectively translate small-scale physical processes to field-scale predictions. Ultimately, the path forward lies in a closed-loop approach, seamlessly integrating fundamental laboratory research, advanced numerical modeling, and carefully monitored field pilots to transform the immense potential of gas hydrates into a safe, predictable, and sustainable energy resource.

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Conflict of interest

The authors declare no competing interest.

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