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Editorial

Natural gas hydrate resource development: Prospects, technical bottlenecks, and research pathways

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Natural gas hydrate is a special gas-bearing solid substance in the shallow layers of the Earth, primarily occurring in sediments along deep-water continental margins and in terrestrial permafrost regions. It is considered not only a conventional natural gas resource with significant potential but also closely linked to submarine methane cycling, sediment stability, marine geohazards, and global climate change. Owing to its combined resource, environmental, and engineering attributes, research on natural gas hydrate has gradually moved beyond the scope of energy development alone, emerging as an important interdisciplinary field connecting Earth sciences, energy engineering, marine technology, and carbon-neutrality strategies.

Over the past decades, significant progress has been made internationally in natural gas hydrate research. Many countries have conducted drilling, coring, logging, seismic surveys, and production tests in marine areas and permafrost regions, providing deeper understanding of hydrate occurrence, resource potential, and development challenges. Field experience has shown that hydrate cannot be treated as a conventional oil or gas resource. Its reservoirs are generally shallow, weakly cemented, highly heterogeneous, and extremely sensitive to temperature, pressure, and engineering disturbances. Production can trigger a series of complex processes, including hydrate dissociation, gas and water production, pore-structure reconstruction, changes in effective stress, sand production, and formation instability. How to achieve safe, efficient, and controllable development while accurately assessing resource potential remains the central challenge for industrializing natural gas hydrate.

The northern continental slope of the South China Sea is one of the world's most important regions for natural gas

hydrate research. Recent geological surveys, production tests, and fundamental studies in areas such as Shenhu, Dongsha, and Qiongdongnan have significantly advanced China's scientific understanding and engineering technology related to hydrates. These studies indicate that hydrate systems in the South China Sea involve complex gas-source conditions, fluid-migration pathways, and tectonic–sedimentary controls. Their reservoir types and engineering geological characteristics impose higher requirements on exploration, evaluation, and development strategies. A key understanding has emerged: Natural gas hydrate research must shift from static resource description to dynamic system understanding, from single-discipline interpretation to multiphysics coupling analysis, and from laboratory-scale exploration to field-scale engineering verification.

In this context, it is necessary to re-examine the scientific significance and engineering challenges of natural gas hydrate from a more integrated perspective. Discussions are no longer limited to resource scale and distribution but are increasingly addressing deeper issues such as the formation and evolution of hydrate systems, reservoir responses, engineering disturbances, environmental impacts, and low-carbon utilization. The primary focus is to understand this highly sensitive natural system and coordinate resource use, environmental safety, and low-carbon development under controllable-risk conditions.

The complexity of natural gas hydrate research stems largely from the dynamic nature of its geological setting. Hydrate formation and accumulation are not solely determined by temperature and pressure conditions but result from long-term coupling of gas supply, fluid migration, sedimentation, tectonic activity, thermal state, and reservoir properties. In deep-water slope environments, deep-sourced gas may migrate upward along faults or high-permeability pathways, while sediment burial and migration of the hydrate stability zone continuously modify hydrate occurrence. Free

gas, dissolved gas, and solid hydrate may undergo continuous interconversion. Therefore, understanding hydrate resources requires clarification of the mechanisms of enrichment, evolution, and responses to external perturbations.

This dynamic nature also defines the unique challenges of hydrate development compared to conventional oil and gas. Hydrate reservoirs commonly exhibit weak cementation, low permeability, strong heterogeneity, and sensitivity to temperature and pressure. Any changes in temperature, pressure, or fluid conditions during production may simultaneously alter pore structure, flow capacity, and formation stress. Although depressurization, heating, replacement, or combined production methods can promote hydrate dissociation and methane release, gas and water production, sand production, wellbore instability, and formation deformation often occur simultaneously and interactively. Consequently, the key to hydrate development is not merely achieving high production but balancing productivity, stability, and environmental safety.

To address these challenges, hydrate research is increasingly adopting multiscale observations and integrated methodologies. Seismic surveys, logging, coring, and *in-situ* testing provide fundamental reservoir data; laboratory experiments and numerical simulations help reveal reservoir response mechanisms; molecular simulations and artificial intelligence methods offer new tools for understanding micro-scale processes, improving identification accuracy, and enhancing predictive capabilities. For fine-grained, weakly consolidated, and highly heterogeneous marine hydrate reservoirs, a single observation or model is insufficient to capture their complexity. Only by integrating field data, experimental results, and theoretical models can resource assessments reflect true geological conditions and development strategies meet safety and efficiency requirements.

Furthermore, hydrate research is closely linked to carbon-neutrality initiatives. Carbon dioxide hydrate storage,

methane–carbon dioxide replacement, and phase transitions of gas hydrate in seafloor sediments provide new directions for low-carbon energy systems. Compared with conventional geological storage, hydrate-based storage offers potential advantages in phase stability and self-sealing. However, efficiency and safety remain constrained by pressure, temperature, salinity, sediment type, pore structure, and submarine tectonics. Although still at an exploratory stage, this research extends the significance of natural gas hydrate science beyond energy production.

The future development of natural gas hydrate requires scientific prudence and engineering patience. A large resource base does not imply rapid commercialization, and successful production tests do not equate to industrial maturity. Current priorities include elucidating formation and evolution mechanisms in typical marine hydrate systems, improving reservoir parameter acquisition and *in-situ* monitoring, developing multiphysics coupling prediction models, and achieving breakthroughs in safe drilling and production, pressure-core preservation, reservoir protection, and environmental risk control. Only by fostering positive interactions among fundamental understanding, engineering technology, and environmental constraints can natural gas hydrate become a reliable component of future energy systems and marine resource development.

This collection of papers aims to provide readers with a window into recent advances in natural gas hydrate research and to offer valuable references for further exploration. We acknowledge the efforts of all authors, reviewers, and editors and hope that these studies will promote deeper discussion of scientific issues and advance hydrate research in China and internationally toward a more systematic, refined, and sustainable direction.

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