Marine Methane Hydrate-Bearing Sediments: A Review of Physical-Mechanical Properties and Exploitation Technologies

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Abstract: Given the advancement of society and the mounting consumption of energy, the reserves of coal, oil, natural gas and other traditional fossil energies are limited and are tending to be exhausted. Although hydropower, wind power, photovoltaic, hydrogen and other new energies have achieved rapid development, their energy supply proportion is still relatively low. At present, the global energy consumption mainly depends on fossil energy. This creates an pressing need to identify a new alternative energy source moving forward. With its enormous resource base, high heating value, and low pollution characteristics, methane hydrate is considered worldwide as one of the most promising substitutes for conventional petroleum among new fossil energy sources. However, occurrence patterns of methane hydrate are diverse, and the processes of hydrate formation and dissociation tend to be highly sensitive to changes in temperature and pressure conditions. Furthermore, the mechanical behavior of methane hydrate-bearing sediments is distinctive. As hydrate saturation changes, so do key properties such as stiffness, dilation, shear strength, and cohesion, resulting in currently the mining of methane hydrate is expensive and difficult. This article will show a brief review and summary of the occurrence patterns, physical and mechanical properties, commonly used mining technologies, as well as research hotspots, thereby offering a reference for future investigations into both the physical and mechanical behavior of methane hydrate and the methods for its extraction.

1. Introduction

Methane gas hydrate forms an ice-like crystalline structure, created when methane and water combine under conditions of high pressure and low temperature. Because it resembles ice in appearance and burns when exposed to fire, it is also called "combustible ice." Natural gas hydrate is found extensively in sedimentary deposits at water depths ranging from 300~3000 meter and burial depths from 0~1000 meter below the seafloor, as well as in permafrost at depths of several hundred meters on land. Global occurrences of natural gas hydrate are mainly concentrated in two types of settings: permanently frozen ground in the Arctic and submarine environments including continental shelves, seafloors, and ocean trenches.

The resource potential of "combustible ice" is enormous. To put it in perspective, its total carbon is estimated to be about twice that of all known fossil fuel reserves—coal, oil, and natural gas combined. Moreover, under standard temperature and pressure, decomposing one unit volume of natural gas hydrate yields roughly 164 unit volumes of methane gas. Its energy density is much higher than that of coal, oil, and natural gas. Moreover, it burns with almost no residual ash or exhaust emissions, resulting in much less pollution than traditional fossil energy sources. This explains why it has gained worldwide acceptance as an alternative energy source to replace coal, oil, and other traditional fossil fuels in the years ahead. With great energy prospects, natural gas hydrate warrants in-depth research to achieve rational and commercial exploitation.

2. Physical and Mechanical Properties

2.1 Occurrence

Formed under deep sea conditions of elevated pressure and reduced temperature, combustible ice presents as a solid, ice - like crystalline phase. Its internal structure features extensive water molecules that are strongly interconnected by both hydrogen bonds and van der Waals forces. The most typical hydrate crystal structures of this substance are SI, SII, and SH. In its natural state, combustible ice occurs mainly in three forms: cemented, pore-filling, and load-bearing types [1], as shown below in Fig. 1.

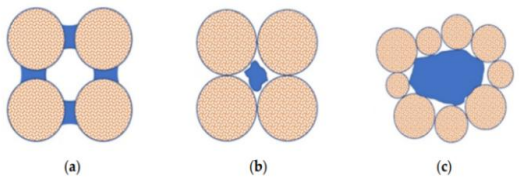

Fig. 1. Occurrence forms of combustible ice. (a) Cemented type; (b) Pore filling type; (c) Load bearing type

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In the cemented type, a small amount of hydrate suffices to significantly boost the shear strength and stiffness of the sediment. This enhancement occurs because the hydrate acts as a binder that locks adjacent grains together. In contrast, the pore-filling type involves hydrate growth along particle boundaries and into the pore space without bonding multiple particles. In this scenario, the hydrate mainly influences the overall stiffness and the fluid conductivity of the pore fluid. For the load bearing type, hydrate increases the mechanical stability of the sediment skeleton. When saturation is high, hydrate naturally transforms into part of the load bearing framework.

2.2 Formation Influence Factors

The formation of hydrates depends heavily on how soluble gas is in water, with temperature, pressure, salinity, and suction also playing significant roles. In the presence of hydrate, generally, an increase in temperature causes more methane molecules to dissolve into the water, reducing the hydrate content. Conversely, an increase in pressure promotes hydrate formation [2]. Although the effect of salinity is less significant than that of temperature and pressure, an increase in salinity reduces the solubility of methane in water, thereby increasing hydrate content [3-4]. Furthermore, the effect of suction is related to pore size; the influence of suction tends to be more significant in sediments with smaller pore sizes, as a general trend [5].

Among above factors, natural gas hydrate is most significantly influenced by pressure (P) and temperature (T). Both permafrost and marine methane hydrate (i.e. the two primary occurrence forms of natural gas hydrate) exist only within the P-T stability zone (see Fig. 2). They differ significantly in terms of occurrence environment, gas composition, and formation mechanism. Permafrost methane hydrate is mainly distributed beneath permafrost layers in polar regions and high-altitude areas, such as the Qinghai-Tibet Plateau and Siberia, with a relatively shallow burial depth (typically 130 to 400 meters underground). Its gas composition is relatively complex, with a methane content of approximately 70% or more, often mixed with heavy hydrocarbon components such as ethane and propane. The gas source primarily comes from the thermogenic decomposition of deep organic matter and is closely related to coal or oil and gas resources. In contrast, marine methane hydrate is widely hosted in deep-sea sediments along continental margins, typically occurring at water depths of over 1,000 meters and buried 200 to 600 meters below the seafloor. Its methane purity is extremely high (approximately 99%), with the gas source mainly derived from the microbial degradation of organic matter, supplemented by a small amount of deep thermogenic gas. In terms of extraction difficulty, permafrost methane hydrate involves relatively lower engineering risks due to the more controllable land environment; whereas the extraction of marine methane hydrate faces prominent challenges such as severe sand production, stratigraphic instability, and methane leakage, resulting in higher technical difficulty and greater environmental impacts. Overall, approximately 97% of the world's methane hydrate resources are stored in marine environments, while permafrost regions account for only about 3%. The discussion in this paper will center primarily on methane hydrate found in marine settings.

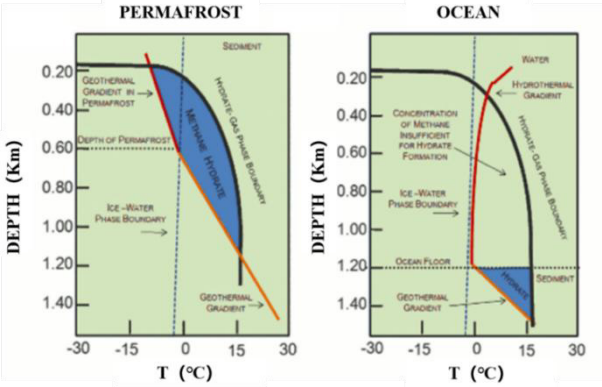
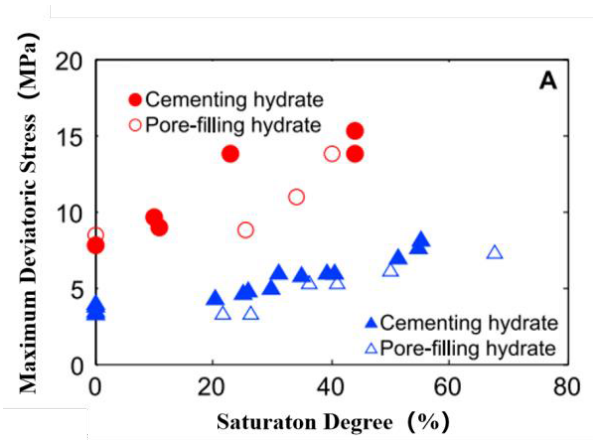


Fig. 2. Methane hydrate stability zone diagram

2.3 Mechanical Properties

Understanding how hydrate-bearing sediment layers deform and assessing their stability during extraction both benefit from research into their mechanical properties. For strength testing, either undisturbed or remolded soil samples can be used on natural gas hydrate-bearing layers. Undisturbed specimens can be obtained using pressure-preserving sampling techniques, although some disturbance remains unavoidable. For remolded samples, hydrate formation is frequently achieved using approaches including the dissolved gas method, partial water saturation, ice seeding, and hydrate premixing.

Methane hydrate generally exerts a strong control over the physical and mechanical behavior of the host sediment layer. While coarse-grained hydrate-bearing sediments have received substantial attention regarding their strength properties, fine-grained counterparts remain comparatively understudied. For hydrate-bearing coarse-grained sediments, a consistent pattern emerges with increasing hydrate saturation under both drained and undrained conditions: stiffness, dilatancy, shear strength, and cohesion all rise, whereas Poisson's ratio and the friction angle show little to no dependence on hydrate saturation [6-10]. These trends are illustrated in Fig. 3 and Fig. 4.



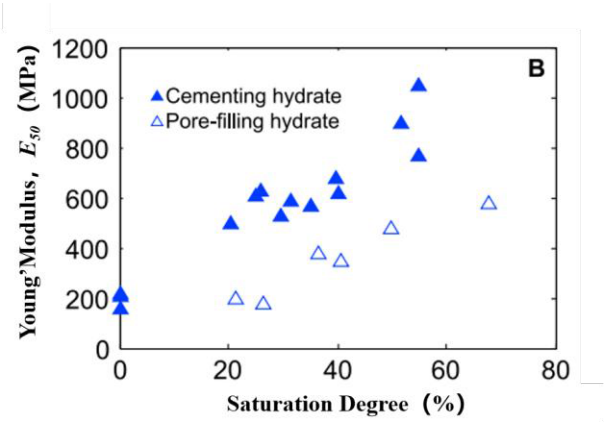


Fig. 3. Correlation among shear strength, Young's modulus E50, and hydrate saturation [10]

Mechanical response of hydrate-bearing sediments depends partly on hydrate morphology, as illustrated in Fig. 3. Cemented hydrates produce a stronger effect on these properties than pore-filling hydrates do, whereas both occurrence forms leave the friction angle and cohesion largely unaffected.

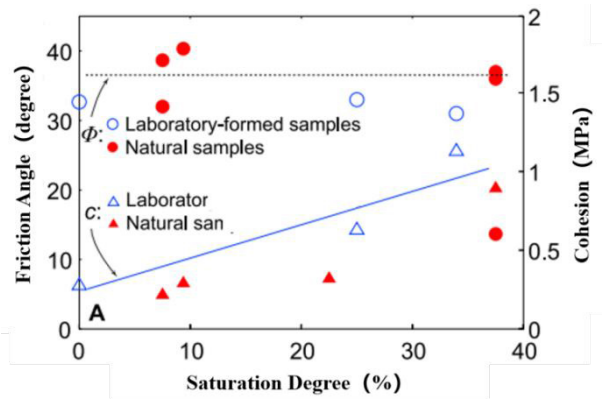


Fig. 4. Correlation of friction angle and cohesion to hydrate saturation in hydrate-bearing sediments [10]

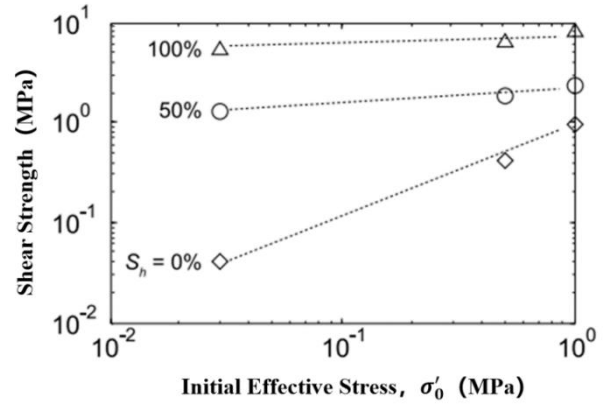


Fig. 5. Undrained shear strength vs. initial effective stress in fine-grained hydrate-bearing sediments with varying hydrate saturation [11]

Research on hydrate-bearing fine-grained sediments remains relatively limited when compared to coarse-grained soils. Nevertheless, as illustrated in Fig. 5, the positive correlation between undrained shear strength and hydrate saturation observed in fine-grained materials closely mirrors that seen in coarse-grained counterparts. Shear strength also rises with increasing initial effective stress; however, this sensitivity to effective stress diminishes notably as hydrate saturation increases [11-12]. Beyond hydrate saturation, additional parameters, namely effective mean stress, confining pressure, temperature, and drainage conditions, also influence the mechanical response of hydrate-bearing sediments.

2.5 Creep Behavior

Furthermore, natural gas hydrate-bearing sediments exhibit creep behavior. Under otherwise identical conditions, different loading frequencies affect the shear strength, with a trend showing that higher shear rates lead to greater shear strength. If a shear rate exchange cycle is imposed, the stress-strain curve will oscillate between two strength envelopes during shearing, as shown in Fig. 6 [13]. The red and blue curves represent two different test groups, each conducted using two alternating shear rates with different periods. Many researchers have taken this phenomenon as a new research focus and have carried out corresponding experimental and constitutive modeling studies [13–15].

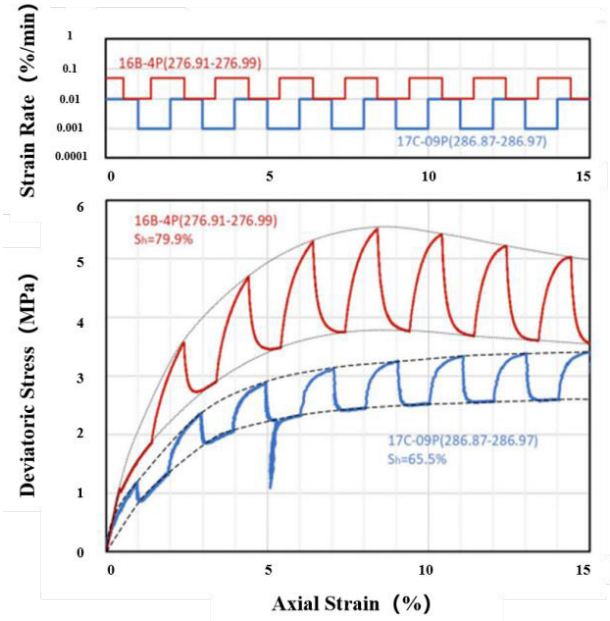


Fig. 6. Stress-strain curves of natural gas hydrate under different shear rates [13]

2.6 Dissociation and Risks

When it comes to the volume change behavior of natural gas hydrate-bearing sediments, most existing work has centered on hydrate dissociation. A decrease in solid hydrate volume occurs when methane hydrate dissociates in response to pressure or temperature variations. This process simultaneously releases gas and water and reduces the salinity of the pore fluid. The sediment's volume, pore fluid pressure, and effective stress are then altered as a consequence of these changes. Under natural conditions, such dissociation typically causes volume contraction, the extent of which varies with sediment type,

stress conditions, porosity, and hydrate distribution. The mechanism underlying this volume contraction is relatively complex and primarily includes bulk hydrate dissociation, changes in the sediment soil skeleton, consolidation, and particle migration (particularly in sandy hydrate-bearing sediments) [16]. In addition to volume contraction, hydrate dissociation also induces a reduction in horizontal effective stress within the sediment and may even trigger internal shear failure [17]. Such changes can lead to submarine engineering accidents such as rupture of submarine pipelines, failure of platform foundations, borehole collapse, and may potentially cause submarine landslides and other forms of marine geological hazards [18].

The formation of these hazards is often a systematic process in which multiple mechanisms are interrelated and evolve progressively. Hydrate decomposition first leads to sediment weakening, meaning that the hydrates, which originally acted as cementation or skeletal support, disappear, resulting in a substantial reduction in the formation's resistance to shear and its overall stiffness. This is followed by changes in pore pressure: if the substantial volume of water and gas released from decomposition fails to be removed promptly, the local pore pressure will rise sharply, reducing the effective stress and even inducing tensile failure. When the area surrounding the wellbore experiences both abnormal pore pressure and weakened formation strength simultaneously, borehole instability occurs, manifested as wall collapse, hole shrinkage, or drilling fluid loss. If the above processes affect a large area and the formation has a slope, the weakened zone may eventually undergo overall sliding, triggering submarine landslides, which can damage submarine infrastructure and generate secondary disasters.

3. Natural gas hydrate extraction

As mentioned above, hydrate is significantly influenced by pressure (P) and temperature (T). Currently, the essence of combustible ice extraction technology is to alter the dynamic equilibrium of combustible ice (i.e., environmental temperature, pressure, etc.) to induce its dissociation into methane gas. Depressurization, thermal stimulation, and chemical reagent injection are the conventional approaches to hydrate extraction. Given the complex physical and mechanical behavior of hydrate-bearing sediments discussed above, it is necessary to conduct borehole stability analysis during extraction operations. Such analysis must take into account how the physical and mechanical properties of the hydrate-bearing layer evolve as extraction progresses.

3.1 Depressurization method

In this method, there are two main approaches to achieve pressure reduction: using low-density mud drilling to reduce pressure, or, when free gas or other fluids exist beneath the hydrate layer, extracting this free gas or these fluids to reduce the pressure within the natural gas hydrate layer. The depressurization method has low operational costs and is suitable for large-scale extraction, particularly in cases where a free gas layer exists beneath the hydrate. Nevertheless, this approach only makes economic sense if the hydrate lies close to the temperature-pressure equilibrium boundary.

Numerous laboratory experiments have investigated depressurization as a production method, with particular attention to how the extent of pressure drawdown, hydrate saturation, and various depressurization schemes affect gas yield [19]. The success of this technique hinges on heat supply throughout the hydrate dissociation process. When no additional heat is provided, especially in the final phases of depressurization, gas production efficiency can be severely compromised. This method was employed at the Messoyakha gas hydrate field in Russia for 17 years, successfully producing 3 billion cubic meters of methane gas.

However, the systematic risks of this method are the most prominent: pore pressure changes directly affect the migration of the dissociation front, which may lead to local overpressure and exacerbate the risk of borehole instability. Long-term depressurization allows the dissociation zone to expand, causing large-scale sediment weakening. If the dissociation zone extends to the slope margin, it may trigger submarine landslides. Therefore, when using the depressurization method, the depressurization rate must be strictly controlled, and sand control measures and formation reinforcement techniques should be implemented.

3.2 Thermal injection method

This method involves directly heating the natural gas hydrate layer to raise the temperature above its equilibrium temperature, thereby inducing hydrate dissociation. Research into thermal stimulation for gas production currently centers on identifying what controls gas output. Key variables under investigation include different sedimentary media and various hot water injection parameters, specifically injection rate, initial temperature, and pressure [20, 21]. To enhance both energy efficiency and production sustainability, two priorities stand out: minimizing heat loss and maximizing gas and water mobility through the reservoir.

Thermal stimulation approach has seen a progression of heating techniques, such as thermal fluid injection, fire flooding, down-hole electromagnetic heating, and microwave heating. Nevertheless, this method continues to suffer from low thermal efficiency and localized heating effects, and thus requires further refinement.

In addition, thermal fluid injection can sharply increase local pore pressure. If production drainage is not smooth, it may easily induce fracture propagation and borehole instability. At the same time, thermal effects may make it difficult to precisely control the dissociation range, increasing the potential risk of large-scale submarine landslides. It is recommended to adopt pulsed thermal injection combined with pressure monitoring to control the dissociation range.

3.3 Chemical reagent injection method

The chemical reagent injection method triggers hydrate dissociation by adding agents like brine, ethanol, methanol, or glycerol into the hydrate layer to destabilize the reservoir's equilibrium [22]. Nonetheless, this approach is hindered by the high cost of chemical reagents and associated environmental issues. The poor gas production performance of chemical reagent injection can be attributed to the low permeability of hydrate-bearing sediments, which limits how efficiently the injected reagents can diffuse. As a result, research efforts in this area have been limited, and the standalone application of chemical reagent injection is deemed unsuitable for commercial development. However, this method can be employed as an auxiliary technique, used in conjunction with depressurization and thermal stimulation methods to enhance natural gas production.

3.4 CH_4-CO_2 replacement method

This method was first proposed by Japanese scholars. The underlying principle is that under certain temperature conditions, CH_4 hydrate requires a higher pressure to remain stable. Therefore, within a certain pressure range, CO_2 hydrate forms more easily and remains more stable. If CO_2 gas is injected into CH_4 hydrate under such conditions, CO_2 hydrate can form while simultaneously displacing CH_4 gas, as shown in Fig. 7.

This method holds great promise for future development, as it enables natural gas hydrate extraction while also addressing the issue of CO_2 solidification and storage, making it a current research hotspot. Numerous scholars have conducted related studies, primarily focusing on CH_4-CO_2 replacement models and extensive experimental investigations aimed at identifying the key factors influencing replacement efficiency. It has been demonstrated that the CH_4-CO_2 replacement process can be markedly enhanced by the addition of auxiliary gases, for example small-molecule gases including N_2, H_2, and He [23]. The pressure of the injected CO_2 gas also has an influence on the replacement process, with higher pressures generally promoting replacement efficiency [24]. Furthermore, many other factors such as porous medium characteristics and hydrate saturation [25-27] also affect replacement efficiency to varying degrees.

Compared with the previous three methods, this method has the lowest geomechanical risks: the formation of CO_2 hydrate can maintain or even enhance the cementation strength of the sediment, partially mitigating the sediment weakening problem; the replacement reaction does not generate excessive free gas, so pore pressure changes are relatively moderate; the risk of borehole instability is significantly reduced due to the mild nature of the reaction process. However, if the replacement efficiency is uneven, local dissociation may still occur in unreacted areas, posing a potential risk of submarine landslides. Overall, this method offers the best geomechanical safety while achieving carbon sequestration.

In addition, other methods include cyclic steam stimulation, dual horizontal well hot water injection, partial oxidation, electrically assisted depressurization, carbon dioxide-assisted depressurization, cold drilling with thermal recovery, and industrial gas replacement.

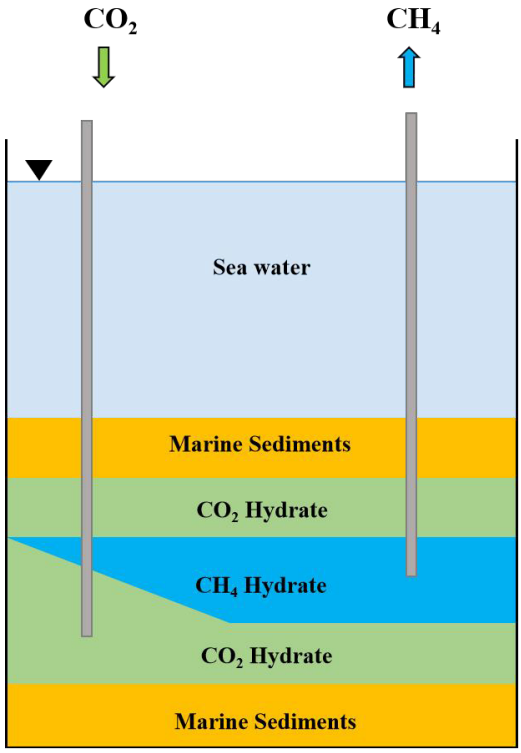


Fig. 7. Schematic illustration of the CH_4-CO_2 replacement approach

Although China started relatively late in the investigation and research of combustible ice resources, it has already taken a leading position in the field of combustible ice extraction technologies. Both land-based permafrost regions and marine offshore areas have seen successful combustible ice trial productions conducted by China to date. In 2020, China conducted a horizontal well trial production of combustible ice using the depressurization method in the South China Sea (Shenhu Area), marking a key shift: moving from offshore pilot exploration to offshore experimental production. China thus became the first country in the world to adopt horizontal well drilling and extraction technology for offshore natural gas hydrate trial production, further enhancing its international leading position in technological innovation capability for natural gas hydrates.

4. Research hotspots

(1) At the grain and pore scales, examining how hydrates interact with sediments can offer a reliable basis for preliminarily evaluating both gas production approaches and failure scenarios, such as submarine slope failures and borehole collapse.

(2) Predicting the behavior of hydrate-bearing sediments hinges on three key parameters: hydrate saturation, effective stress, and sediment particle size, with particular attention to the proportion of fine-grained silt and clay. The influence of hydrate saturation on

sediment stiffness and strength is not fixed; it varies with the saturation level achieved. Meanwhile, the fine-grained fraction largely determines how hydrates form and how fluids move through the sediment, and it also plays a major role in the cascade of effects triggered by hydrate dissociation. Therefore, more research in this direction is needed.

(3) Natural gas hydrates are prone to sample disturbance. The development of novel in-situ testing methods and pressure-preserving sampling equipment and techniques will enable more direct and accurate characterization of the physical and mechanical properties, thereby providing fundamental support for hydrate extraction.

(4) The CH_4-CO_2 replacement method exhibits excellent development potential, as it simultaneously addresses combustible ice extraction and CO_2 sequestration. Achieving more efficient and cost-effective replacement has become a current research hotspot.

5. Summary

As an new alternative of fossil energy, natural gas hydrate holds great promise for future applications. However, commercial extraction has not yet been achieved due to current limitations in extraction costs, extraction technology, and efficiency. Further research is needed to understand the physical, mechanical, and dissociation characteristics of combustible ice, and to optimize extraction techniques and processes. On the premise of ensuring operational safety, it is necessary to reduce extraction costs, improve extraction efficiency, and minimize environmental impact. The ultimate goal is to realize true commercial extraction of combustible ice resources at an early date, thereby promoting technological progress in marine development and facilitating the adjustment of China's energy structure. This will provide strong support for the realization of strategic objectives such as the "Maritime Power" initiative, and "carbon peak and carbon neutrality".

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