Research Report on Technologies and Equipment for Exploitation of Marine Combustible Ice Resources

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Abstract. Scientists have been focusing on studying combustible ice as "new energy for the 21st century" due to its wide distribution, abundant reserves, high energy density, low pollution and other advantages. With boundless prospects, however, combustible ice has posed a severe challenge to the existing science and technology of human. Its exploitation technologies have become a key academic research field in the new century. Therefore, it is of vital importance to master scientific payoffs and development trends of Chinese domestic and foreign technologies and equipment for the exploitation of combustible ice and make breakthroughs in its drilling techniques in order to address the energy crisis and carry out the strategic action plan for energy development better in China.

1. Introduction

Combustible ice, also known as natural gas hydrate, is a crystalline substance similar to ice formed by natural gas and water under low-temperature and high-pressure conditions, which has many advantages such as wide distribution, abundant reserves, high energy density and low pollution and generally exists on the seabed or terrestrial permafrost. About 27% of the land and 90% of the ocean on the earth contain combustible ice, resulting in global reserves of 20,000×1012 m3. Its carbon content is more than twice the total carbon content of all proven fossil fuels[1]. Combustible ice is internationally recognized as an alternative energy source for oil and natural gas[2] and is praised by scientists as "future energy" and "energy for the 21st century" as its abundant reserves can satisfy human needs for a thousand years.

Just because of so many performance advantages above, its exploitation techniques have been being studied in detail in all academic circles around the world and have become another major subject in the 21st century though its exploitation may bring about side effects such as greenhouse effect, submarine slide, tsunami and damage to marine ecological balance[3].
2. Introduction to combustible ice

![Figure 1 Combustible ice](image)

2.1. Formation of combustible ice
Combustible ice must form at a low temperature ranging from 0 to 10 °C and high pressure over 10 MPa, under the prerequisite of adequate air and water and with a certain void structure for its growth[4]. It is easily decomposed at a temperature above 20 °C and may form only under more than 30 atm at 0 °C. Besides, the geological structure, water-bearing media and the pH value are also important factors influencing the formation of combustible ice. Figure 1 shows the appearance of combustible ice.

2.2. Distribution of marine combustible ice
From the global perspective, combustible ice is mainly distributed in the Bering Sea, the Sea of Okhotsk, the Kuril Trench, the Okinawa Trough, the Nankai Trough, Japan, the Shikoku Trough, the Sulawesi Sea, the Ulleung Basin, South Korea and the North Island, New Zealand in the Western Pacific Ocean, the Blake Ridge, the Gulf of Mexico, the Caribbean Sea, the outer continental margin of the East Coast of South America and waters off the West Coast of Africa in the Atlantic Ocean, the Middle America Trough, the Northern California-Oregon Coast and the Peru Trough in the East Pacific Ocean, the Gulf of Oman in the Indian Ocean, the Barents Sea and the Beaufort Sea in the Arctic, the Ross Sea and the Weddell Sea in the Antarctic, the Black Sea and the Caspian Sea, etc.[5] The targets and scope of combustible ice exploration in the United States, Russia, Canada, the Netherlands, Japan, India and other countries cover almost all important potential areas in the continental margin of seas, permafrost zones in high-altitude polar regions and Antarctic continental margins[6]. They have successively incorporated their detailed development roadmaps into the national medium- and long-term energy development plan and have proved by seismic exploration that a lot of combustible ice is forming in the Arctic region[7].

3. Exploitation technologies and principles of marine combustible ice
It is most difficult in marine combustible ice exploitation to ensure the stability of the bottomhole so as to prevent leakage of methane gas and the greenhouse effect.
3.1. Traditional exploitation methods

3.1.1. Thermal excitation method
In this method, the natural gas hydrate reservoir is heated directly to a temperature higher than its equilibrium temperature, which facilitates the decomposition of natural gas hydrates into water and natural gas. The heating mode has experienced the development process from direct injection of hot fluids into natural gas hydrates, fire flooding and downhole electromagnetic heating to microwave heating. The method can realize cyclic heat injection and can function rapidly. The constant improvement of the heating mode has accelerated the development of exploitation with the thermal excitation method. However, this method has not yet solved the problem of low heat utilization efficiency and only allows local heating, and therefore needs to be further improved.

3.1.2. Decompression method
In the decompression method, the decomposition of natural gas hydrates is prompted by pressure reduction. That is, combustible ice is decompressed with a physical method to achieve the purpose of decomposition. There are two main ways of decompression:

① Drilling with low-density slurry to achieve the purpose of decompression; and
② Pumpout of free gases or other fluids below the natural gas hydrate reservoir, if any, to reduce its pressure.

With no need for continuous excitation and at low costs, the decompression method is applicable to wide exploitation, especially the exploitation of natural gas hydrate reserves in the reservoir with free gases below, and is the most promising technology among traditional exploitation methods of natural gas hydrates. However, it has special requirements for the nature of natural gas hydrate reserves. It is economically feasible only when natural gas hydrate reserves are located near the steady-pressure equilibrium boundary.

3.1.3. Chemical reagent injection method
In this method, some chemical reagents such as saline, methanol, ethanol, ethylene glycol and glycerol are injected into the natural gas hydrate reservoir to damage the equilibrium condition of natural gas hydrates and push their decomposition. Though with less initial energy input, the method has obvious defects including high costs of chemical reagents required, slow action on the natural gas hydrate reservoir and environmental problems. Therefore, there are fewer relevant studies. Only some chemical reagents are added to combustible ice to transform "ice" into gas.

3.2. New exploitation methods

3.2.1. CO2 replacement method
This technique is still based on the pressure condition of the natural gas hydrate stability zone. Natural gas hydrates require higher pressure than CO2 to keep stable under certain temperature conditions. Therefore, they will decompose within a specific pressure range while CO2 hydrates will form easily and remain stable. CO2 gas, if injected into natural gas hydrates, may react with the water decomposed from the latter to generate CO2 hydrates.

3.2.2. Solid exploitation method
In the original solid exploitation method, solid natural gas hydrates on the seabed were collected directly and dragged to shallow water for controlled decomposition. The method has then evolved into the combined exploitation method. To be more specific, natural gas hydrates are first made to decompose into gas-liquid mixed phases in situ and the mixed mud containing gas-liquid-solid hydrates is collected and then poured into a service vessel or production platform at sea for treatment to promote complete decomposition of natural gas hydrates.
Combustible ice in the South China Sea has a small burial depth and weak cementation and is easy to fragment, which is very suitable for the use of solid fluidization method. Therefore, the method has aroused the research interest of many Chinese scholars after put forward. In April 2015, the Southwest Petroleum University established the world's first Laboratory for Solid Fluidization Exploitation of Marine Non-diagenetic Natural Gas Hydrates, which can prepare large-volume solid hydrates, grade the rock breaking capacity of exploitation equipment, evaluate the rock carrying capacity of hydrate fluidization, simulate the pipeline transmission process of hydrates and study the law of hydrate decomposition and rheological laws. It is reported that China carried out trial production successfully in the north of the South China Sea with the solid fluidization technology for the first time in May 2017, obtaining 81 m³ gases at a purity of up to 99.8%. The field trial production has proved the feasibility of the solid fluidization method in the exploitation of shallow non-diagenetic combustible ice[8].

3.2.3. Combined exploitation method
The hydrate exploitation process tends to have two or more methods combined, among which the decompression method is generally dominant, so as to improve the exploitation efficiency, safety and applicability. Common combined exploitation methods include hot-water injection using dual horizontal wells, partial oxidation, electric heating supplemented by decompression, CO² replacement supplemented by decompression and combined mechanical-thermal exploitation, etc.[8]

3.3. Overview of artificial combustible ice
As a natural gas hydrate, artificial combustible ice is a crystalline cage solid formed by artificial combination of methane molecules in natural gas with free water under the action of kinetic and thermodynamic additives under certain temperature and pressure conditions.

Artificial combustible ice is similar to natural combustible ice in physics, chemistry, structure and properties, but is featured with short time of formation, high gas density, low cost, high efficiency, transport convenience and strong replaceability. It is likely to become a special development and utilization method in energy transformation and upgrading of China in the future[9].

4. Exploitation equipment for marine combustible ice
A natural gas hydrate is a phase state of natural gas under certain temperature and pressure conditions. Therefore, its exploitation equipment and corresponding devices and systems are the same as most offshore oil and gas development equipment. They are different in the analysis mode, heat and pressure preservation measures, monitoring system and other aspects due to their respective characteristics. However, most equipment applicable to the exploitation of natural gas hydrates can be used after improved with the existing equipment on the whole.

Two measures shall be taken to ensure the supply of equipment after commercial exploitation based on the reservoir forming characteristics of natural gas hydrates. On the one hand, the existing equipment shall be modified in terms of the adaptability to the exploitation of natural gas hydrates, including the update of drilling and completion, production and monitoring systems and other systems and equipment and the modification of other components adapted to the development of natural gas hydrates. On the other hand, new natural gas hydrate exploitation equipment shall be designed, such as trial production equipment of natural gas hydrates with drilling and completion, production, storage and unloading and other functions, light drilling equipment with a smaller drilling depth and greater flexibility as well as mining equipment suitable for the exploitation of shallow non-diagenetic hydrates[10].

For this reason, most of the current exploration and exploitation equipment of combustible ice is converted from previous advanced scientific expedition vessels by equipment configuration.
4.1. Bluewhale 1

Bluewhale 1, as shown in Figure 2, is a semi-submersible drilling platform with the largest operating water depth and drilling depth around the world, which is applicable to global deep-water operations and the empty weight of which is 42,000 tons. Its deck area is equivalent to a standard football field. The platform is 117 m long, 92.7 m wide and 118 m high and the height from the hull bottom to the top of the rig is that of 37 floors. Its maximum operating water depth is 3,658 m and its drilling depth can reach 15,240 m, much more than the deepest trench in the world, the Mariana Trench, with an elevation of -11,034 m[11].

The news of China's first successful trial production of combustible ice in the Shenhu area of the South China Sea spread all over the world in May 2017. Bluewhale 1, the ultra-deepwater semi-submersible drilling platform with dual derricks undertaking the major national strategic mission, has once again attracted global attention. It represents the highest level of design and construction of offshore drilling platforms in the world today, making China rank among the world top in terms of the capacity of deepwater oil and gas exploration and development, and is also important practice of China International Marine Containers Co., Ltd. (CIMC) in the implementation of the national grand strategy "the Belt and Road Initiative" and the improvement of the national strength in high-end energy equipment.
4.2. **JOIDES Resolution ocean drillship**

![JOIDES Resolution drillship](image)

The JOIDES Resolution drillship is a drilling ship used in the ocean drilling program and the integrated ocean drilling program as well as one of the most advanced ocean drilling ships in the world. Figure 3 shows its general structure.

JOIDES Resolution, with a total displacement of 9,050 tons, 143 m long and 21 m wide, can sail continuously for 75 days at sea. Its derrick, 61.5 m high, can operate 9,150 m drill strings, and its drilling capacity is 9,150 m. The maximum drilling depth is 8,235 m and the maximum drilling depth under the sea is about 4,000 m. The ship is equipped with 12 powerful propellers for dynamic positioning and the world's largest lift compensation device with a lifting capacity up to 400 tons. It also includes a seven-storey laboratory covering an area of 1,400 m² for analysis and research in sedimentology, petrology, paleontology, geochemistry and geophysics. The ship has repeatedly carried out combustible ice exploration missions in Japan, the United States, New Zealand and other places, turning into a "senior" in combustible ice exploration activities.

4.3. **CHIKYU deepsea drilling vessel**

![CHIKYU deepsea drilling vessel](image)

CHIKYU is the world's largest deepsea drilling vessel made in Japan, which has set the world's deepest seafloor drilling record at 7,740 m. CHIKYU is known as the first multifunctional scientific drilling vessel in human history as it is capable of large-depth drilling operations in the mantle and regions where violent earthquakes occur, etc.

As one of the world's largest drilling vessels, CHIKYU has 5 floors above water and 3 floors underwater and has a total length of 210 m, a width of 38 m, a draught of 9.2 m, a total tonnage of about 57,000 tons and a full load endurance capacity of about 14,800 sea miles. Its maximum speed per hour can reach 12 kn. The high and big rig for drilling in the middle is 130 m high (calculated from the hull bottom). Figure 4 shows the full view of CHIKYU.
As one of the few large-scale drilling ships in the world that can explore combustible ice, the CHIKYU drillship has carried out combustible ice exploration and sampling activities in the waters around Japan for many times.

5. Status and trend in China and foreign countries

5.1. Development status of foreign combustible ice

A craze for the exploitation of combustible ice has been set off around the world by the advantages of combustible ice such as cleanliness and non-pollution, wide distribution and abundant resources plus the determination of seeking for alternative energy. Investigation shows that more than 30 countries have studied and analyzed physical properties of combustible ice so far. Development, testing and exploration technologies of combustible ice have been increasingly mature with the constant development of science and technology, but technologies for safe commercial exploitation of combustible ice still require continuous improvement and innovation.

Table 1 Development status of foreign combustible ice

| Country          | The main research results                                                                 |
|------------------|------------------------------------------------------------------------------------------|
| Former Soviet Union | 1960-Discovery of the world's first combustible ice deposit in Siberia                     |
|                  | 1970-30 years of exploration of gas hydrate in the Mesoyaha gas field in the Siberian tundra have been carried out. |
|                  | 1969-Conducted investigations on combustible ice.                                         |
|                  | 1981-Proposed a ten-year exploration project plan for combustible ice.                    |
|                  | 1998-Listed combustible ice as a national strategic project.                               |
|                  | 2001-Analysis of the characteristics of combustible ice structures on the northern border of Alaska. |
| USA              | 2003-Listed combustible ice as a national strategic project.                               |
|                  | 2005-Found in the Gulf of Mexico and proved that combustible ice in sand can be mined.    |
| Japan            | 2002-Began to pay attention to the field of combustible ice.                               |
|                  | 2000-Began to investigate the reserves and distribution of combustible ice on the seabed. |
|                  | 2012-Completed commercial drilling for the first time in Japanese waters.                 |
|                  | 2013-The world’s first submarine combustible ice was mined in Atsumi Sea Hill.           |
|                  | 2017-Carried out the second productive experiment on submarine combustible ice.          |
|                  | 2018-Improved mining technology and realized full commercial production.                   |

Table 1 shows the development status of combustible ice in some major countries. Moreover, India established a five-year National Research Program for Gas Hydrates in 1995, conducted a research on physical properties of natural gas hydrates in 1997 and obtained natural gas hydrate samples in 2006, speculating the reserves of about 1,894 trillion m³. South Korea acquired natural gas hydrate samples in 2007, and verified mining areas of combustible ice in surrounding waters and estimated its reserves preliminarily in 2008. Some developed countries and international organizations have also carried out the work such as explorations and researches on natural gas hydrate energy and technical reserve of development[12-14].
5.2. Development status of combustible ice in China

Table 2 Development status of combustible ice in China

| Time       | The main research results                                                                 |
|------------|------------------------------------------------------------------------------------------|
| The late 1980s | Began to focus on combustible ice and collect data.                                    |
| 1988       | For the first time, the formation conditions of combustible ice in the surrounding sea area were summarized and analyzed. |
| 1999       | The presence of combustible ice in the South China Sea has been confirmed for the first time. |
| 2002       | The reserves of combustible ice in the South China Sea were investigated, and the coal deposits in Xisha Trough were determined. |
| 2005       | Exploration of combustible ice development areas in the South China Sea.                |
| 2006       | Combustible ice samples were first obtained in the South China Sea.                     |
| 2007       | Samples of combustible ice have been obtained from the Permafrost of the Qilian Mountains, making China the first country in the world to find combustible ice in the tundra of low and middle latitudes. |
| 2015       | For the first time in China, combustible ice was synthesized artificially.              |
| 2017       | The blue Whale 1 drilling rig has made its first successful test run in the South China Sea. |

Permafrost zones in China cover an area of $2.15 \times 10^6$ km$^2$, containing combustible ice of up to $3.5 \times 10^{10}$ t oil equivalent, while Chinese waters contain $4 \times 10^9$ t oil equivalent, according to investigation. The study on combustible ice has made some progress and the gap in exploration and development technologies is narrowing gradually with the expansion of international R&D cooperation and the importance attached to industrial development of combustible ice by the Chinese state in recent years, though China started late in combustible ice survey and research compared to developed countries\[15\]. Table 2 shows the development status of combustible ice in China.

China has set two new world records for "total gas production and average daily gas production" in the Shenhu area of the South China Sea so far, making significant breakthroughs in the process from "exploratory trial production" to "experimental trial production". The total gas production and the average daily gas production in the one-month trial production, i.e. 861,400 m$^3$ and 28,700 m$^3$ respectively, are leading in the world. China has meanwhile overcome difficulties in core and key technologies for horizontal well drilling in deepwater shallow soft strata and become the world's first country using horizontal well drilling techniques for trial production of natural gas hydrates in waters. China's strategic development plan and natural gas hydrate research and development plan indicate that the period from 2006 to 2020 is the preliminary exploration stage and that from 2020 to 2030 is the initial stage of exploitation, and that the development of combustible ice in China will enter the stage of commercial exploitation by 2050\[14\].

5.3. Major gas hydrate drilling activities in the world

Combustible ice drilling is still in full swing in the world. Table 3 lists the important drilling activities that have been carried out mainly for the exploration and evaluation of marine hydrate resources\[16\].


6. Existing technical bottlenecks

Main technical bottlenecks in the development and utilization for the purpose of effective collection of the methane gas released by combustible ice without any great harm to the climate and ecology include techniques of geophysical exploration, geochemical exploration, borehole sampling, resource evaluation, mining, laboratory simulation, transportation and storage, and detection and removal of hydrates in pipelines [17].

The geophysical exploration technique includes methods such as multi-channel seismic reflection exploration and logging. The geochemical exploration technique includes the reduction of salinity or chlorinity of pore water in sediments containing "combustible ice" and the decrease of oxidation-reduction potential and sulfate content of water. For the borehole sample technique, a fidelity coring barrel is developed for sampling. In respect of the resource evaluation technique, on the one hand, relevant parameters of the "combustible ice" reservoir are obtained through geological and geophysical exploration and drilling, its distribution is predicted and the amount of resources is calculated; on the other hand, a mathematical model for the formation and gas release of "combustible ice" is established based on actual parameters obtained and simulation experiments, and its distribution and resource quantity are studied with numerical simulation methods. "Combustible ice" exploitation technologies can be roughly divided into thermal excitation, chemical reagent injection, decompression, CO2 replacement and solid exploitation methods. In terms of the laboratory simulation technique, conditions for the formation and steady distribution of "combustible ice" are studied through changes in temperature, pressure, natural gas composition, fluid composition and other boundary conditions by physical-chemical means. For the technique of detection and removal of hydrates in pipelines, anti-coagulants are developed to clear obstacles. The development of "combustible ice" also involves many relevant technologies such as storage and transportation technologies [18].

7. Conclusions and suggestions

7.1. Conclusions

The following conclusions can be made based on the knowledge acquired in class and the study on relevant literature:
① Compared to other energy, combustible ice is a cleaner and better new energy resource with abundant reserves, high energy density, low pollution and other advantages.

② China is very abundant in combustible ice. A lot of combustible ice is widely distributed in permafrost regions of Tibet, on the floor of the South China Sea and in the East China Sea, which can meet the normal development demand of China if fully exploited.

③ There is a long way to go before technical bottlenecks are relieved as the technologies for marine combustible ice exploitation are very complicated and a lot of potential safety hazards and environmental pollution issues exist during exploitation.

④ China has made rapid progress and has been narrowing the gap with other countries though it started late in the field of combustible ice exploitation techniques.

⑤ China, with the Bluewhale 1 drilling platform in the first echelon of the world, is fully capable of independent research and development in equipment for marine combustible ice exploration.

⑥ Huge investment has been made in combustible ice exploitation both in China and foreign countries. The industry of marine combustible ice exploitation is flourishing, and its industrialization and product commercialization are just around the corner.

7.2. Suggestions

Suggestions below are hereby made in order to make full use of existing combustible ice resources, improve the ability of China in combustible ice exploration and exploitation and thus solve energy crisis problems to be confronted by human:

① Increase input in the study on technologies for marine combustible ice exploration and exploitation to accelerate commercial exploitation of marine combustible ice and allow combustible ice to actually benefit human rather than only exist in textbooks.

② Make relevant policies and provide convenience for preferential development of the marine combustible ice exploitation sector through government intervention.

③ Cooperate with Japan, the United States and other countries advanced in the field of combustible ice techniques and draw strength from them to narrow the gap between China and such countries and develop the combustible ice industry faster and better.

④ Strengthen media publicity and attract more talents to the industry of marine combustible ice exploration and exploitation.

⑤ Hold combustible ice sci-tech exhibitions regularly to popularize the technical field and facilitate the promotion of products after future commercial exploitation of combustible ice.

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