The distribution of combustible ice and the status of exploitation

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Abstract. The distribution of combustible ice in the world is investigated. The characteristics of different mining methods are clearly defined by the analysis of the successful cases of the development of combustible ice in the United States, Japan, Russia, Canada and India. The distribution rules and the historical process of the development of the combustible ice in China are introduced, the discovery of the combustible ice in the South China sea is analyzed. The analysis of ice production technology, the mining methods, applicable reservoirs and existing problems of combustible ice are expounded. The significance of combustible ice as a new energy to alleviate energy crisis is pointed out.

1. Introduction
Natural gas hydrate, commonly known as combustible ice, is a kind of ice like substance formed by natural gas and water under suitable conditions (usually low temperature and high pressure). In nature, it is mainly distributed in the deep-sea permanent sedimentary strata and the land permafrost zone. At present, combustible ice has been found in more than 70 countries and regions, and at least 30 countries and regions have studied it. According to incomplete statistics, the global combustible ice reserves are about 2.1×1016m3, 130 times of the known remaining natural gas reserves, and the total organic carbon resources are equivalent to 2 times of the global known carbon content of fossil energy, which can be used by human for at least 1000 years [1].

2. Global distribution and development of combustible ice

2.1. Global distribution of combustible ice
Due to the unique formation conditions of combustible ice, the distribution of combustible ice in the land area is significantly less than that in the sea area. 97% of the direct or indirect combustible ice deposits in the world are concentrated in the ocean, and the remaining 3% are mainly located in the land permafrost zone [2]. Among them, the distribution of land is mainly concentrated in the West Siberia of Russia, the great Caucasus Mountains, the north of Alaska in the United States, the Mackenzie River Delta in Canada, the Qilian Mountains and the Qinghai Tibet Plateau in China and other permafrost regions. The sea areas are mainly distributed in the Bering Sea, Okhotsk Sea, Qianao trench, Okinawa Trough, South China Sea trough of Japan, Shigou trough, South China Sea trough, Sulawesi sea, Yulong basin of South Korea and North Island of New Zealand in the Western Pacific Ocean. The black platform, the Gulf of Mexico, the Caribbean Sea, the outer continental margin of the east coast of South America and the west coast of Africa in the Atlantic Ocean. The
Central American trough, the Northern California Oregon offshore, the Peruvian trough, the Oman Bay in the Indian Ocean, the Barents and Beaufort seas in the Arctic, the Ross and Weddell seas in the Antarctic, and the black and Caspian seas [3]. The global distribution of combustible ice is shown in Figure 1. The red areas indicate the identified area, and the yellow areas indicate unexplored areas.

![Figure 1. Global distribution of combustible ice.](image)

2.2. Research status of global combustible ice mining

So far, many times of pilot mining of combustible ice have been successfully carried out in permafrost area and deep water area in the world. The technical feasibility of the main mining methods of combustible ice, such as thermal stimulation method, decompression method and carbon dioxide replacement method, has been preliminarily explored, and successful pilot mining has been realized, as well as successful cases of commercial mining. However, as a whole, the research on combustible ice mining is still in the exploration stage, and there is no technical method or method combination that can economically and effectively mine combustible ice, which is still a long way from the realization of commercial exploitation of combustible ice.

In 1960, Russia discovered the first typical ice gas reservoir with underlying free gas in the masoyaha gas field in the permafrost region of western Siberia. The gas reservoir is located in the permafrost zone in the northwest of West Siberia, with a permafrost thickness of 500m, which is conducive to the occurrence of combustible ice. The free gas in the lower part of the gas reservoir migrates through the caprock, forming a flammable ice layer over the gas field [4]. In the later stage, in order to promote the further decomposition of natural gas hydrate and maintain gas production, chemical inhibitors such as methanol and calcium chloride were injected into the combustible ice gas reservoir. During the 17 years of exploitation, 5.02 × 10⁶ m³ natural gas has been successively exploited [5].

In 1971, Canada drilled the conventional exploration well Malik L-38 in Mackenzie Delta, found evidence of the existence of combustible ice [6], drilled the well Malik 2l-38 in the next year [7], and produced the combustible ice core [8]. In 2002, scientific research institutions from Germany, the United States, India, Canada and Japan jointly participated in the investment to carry out the pilot production of combustible ice in the Mackenzie Delta. Three exploration wells were drilled in this trial production, including malik5l-38 well for trial production study, malik3l-38 well and malik4l-38 well for observation. All three wells drilled through the gas hydrate layer as planned. Two observation wells are used for temperature measurement, seismic measurement and conventional mud gas measurement, so as to find out the location of gas hydrate decomposition and determine the location of gas producing interval [9]. The layout of three exploratory wells is shown in Figure 2. In this area, the test and evaluation of decompression mining method and thermal excitation mining method are carried out respectively [10]. The results show that the efficiency of thermal excitation mining method is low and it is difficult to meet the large-scale commercial mining. The effect of decompression method is better than that of thermal excitation method, but how to supply the heat required for phase transformation of combustible ice in decompression mining is not effectively solved.
Figure 2. Layout of combustible ice test production wells in Canada.

One of the largest conventional oil and gas producing areas in the United States, the exploration and research of combustible ice in the Gulf of Mexico began in the 1980s. In 2001, the U.S. Department of energy launched a "joint industrial project" dedicated to the study of combustible ice in the Gulf of Mexico, which carried out core drilling and logging while drilling research, and confirmed that there is a high saturation and high-quality combustible ice bearing sand layer in the Gulf of Mexico, and at the same time, fracture filled combustible ice has developed in fine-grained sedimentary layer [11]. Following the "joint industrial project" in the Gulf of Mexico, at the end of 2014, the national energy technology laboratory under the U.S. Department of energy established a large-scale project of "description and scientific evaluation of deep-water methane flammable ice". The project is divided into three implementation stages: target station selection, research plan formulation and field research.

By the end of September 2015, the first stage of work has been completed, and the preliminary evaluation of some combustible ice research stations in the Gulf of Mexico has been completed, and the seismic and logging data of the target research stations have been reevaluated. At present, the second stage of research work is in progress. By the end of 2016, the planning work of combustible ice drilling voyage has been submitted to the comprehensive ocean drilling plan, the development of pressure maintaining coring tool has been completed, and the test of the effect of combustible ice coring in the onshore environment has been passed. Now, the test is being carried out in the offshore deep water area to test the effect of combustible ice coring in the deep water environment.

In October 2016, the United States launched a three-year combustible ice research project in the Gulf of Mexico. The electromagnetic method was used to study the conductivity of the combustible ice system in different deposition types and different fluid content environments and the change characteristics of the conductivity of the combustible ice caused by mining. Based on the study of 2-3 prospective sites of combustible ice, the relationship between formation conductivity and logging data is established to improve the accuracy of in-situ resource evaluation of combustible ice [12].

3. Distribution and development of combustible ice in China

3.1. Combustible ice distribution in China

China's combustible ice resources are mainly distributed in the northern slope land of the South China Sea, Qilian Mountain permafrost area, Qinghai Muli permafrost area, the eastern sea area of Pearl River Mouth Basin, Kunlun Mountain Yakou Basin, Qiongdongnan Basin, northeast Mohe Basin, Tainan Basin, Qiangtang Basin, etc. According to the estimation of relevant experts, the total amount of combustible ice resources in China is \(8.41 \times 10^{11} \text{m}^3\), including \(3.4 \times 10^{12} \text{m}^3\) in the East China Sea, \(6.5 \times 10^{13} \text{m}^3\) in the South China Sea, \(1.25 \times 10^{11} \text{m}^3\) in the permafrost zone of the Qinghai Tibet Plateau and \(2.8 \times 10^{12} \text{m}^3\) in the Northeast permafrost zone.
3.2. Research status of combustible ice mining in China

The study of combustible ice exploration began in 1999 in China. The exploration area is concentrated in Dongsha, Shenhu, Xisha and Qiongdongnan. In 2000, Guangzhou Marine Geological survey found a combustible ice belt in the South China Sea and took samples from the sea floor [13]. In 2002, the special investigation and research project of combustible ice resources in China's sea area was launched, and four breakthroughs were made: the discovery of combustible ice prospect in the northern slope of the South China Sea, the evaluation of the potential of combustible ice resources in the northern slope of the South China Sea, the determination of two key targets of combustible ice, Dongsha and Shenhu, and the confirmation of the existence of combustible ice resources in the South China Sea [14].

In 2004, "Jiulong methane reef", the largest known cold spring overflow area in the world, was found in the sea area to the east of Dongsha Islands, and preliminary evidence for the existence of combustible ice on the northern slope of the South China Sea was obtained [15]. In 2007, the first combustible ice drilling voyage gms-1 was carried out in Pearl River Mouth Basin in Shenhu sea area, and three of the eight wells produced combustible ice samples [16]. In 2011, the special project of combustible ice drilling was launched to accelerate the exploration and evaluation of the prospective area of combustible ice resources in the north of the South China Sea, select key target areas, and implement the experimental exploitation of combustible ice. In 2013, the drilling research was carried out in the eastern sea area of the Pearl River Mouth Basin, and the visible high-purity combustible ice was found for the first time. In 2015, in the southwest slope area of Shenhu sea area, the sea bottom "cold spring" was discovered for the first time by using the seahorse submersible, and combustible ice samples were collected by gravity corer.

On May 18, 2017, the trial production of combustible ice in Shenhu sea area was successful, achieving stable gas production for 8 consecutive days, with the cumulative gas production exceeding 120000 cubic meters, the maximum daily gas production reaching 35000 cubic meters, and the average daily gas production of 16000 cubic meters, with the maximum methane content of 99.5%. This pilot production not only achieved continuous and stable gas production for the first time in the study of combustible ice pilot production in the sea area, but also successfully implemented the safe and controllable production test of argillaceous powder sand type combustible ice reservoir in the world, making a historic breakthrough in the study of combustible ice pilot production in the sea area [17].

4. Current situation of combustible ice mining technology

4.1. Step down method

In the free gas enriched formation, the low pressure cavity is formed by reducing the pressure to promote its decomposition. Masoyaha gas field is a successful case of depressurization. Decompression method does not need continuous excitation and is suitable for large area mining. However, the disadvantage of this method is that there is no additional heat to be delivered to the mining layer in the process of implementing the depressurization method, which will cause the combustible ice to absorb a large amount of surrounding heat during decomposition. When the surrounding temperature drops to a certain extent, it will reduce or even inhibit the decomposition of the combustible ice[18,19]. Therefore, only when the temperature pressure equilibrium boundary is easy to reach, the depressurization method has practical value.

4.2. Thermal excitation method

The thermal fluid is pumped from the surface to the reservoir and heated by electromagnetic and microwave, which makes the reservoir temperature rise and decompose. This method was applied in Mackenzie permafrost in 2002. However, its thermal efficiency is low in the process of pilot production[20].
4.3. Method of adding chemical inhibitors
Chemical inhibitors such as methanol and brine are injected into the reservoir to promote its decomposition. The gas production of masoyaha gas field in Russia increased significantly after injection of inhibitor[21-23]. However, the inhibitor has a long time of action and pollutes the environment.

4.4. CO2 replacement method
In a specific pressure range, CH4 in the combustible ice can be replaced by CO2, which is an exothermic process and can maintain the decomposition of the combustible ice. In 2012, ConocoPhillips first conducted field experiments in prudhoe Bay area, north slope of Alaska, and achieved success [24]. However, the replacement rate of this method is too low, and there is still a large space for development.

4.5. Cold drilling and hot production technology
The cold drilling and thermal recovery technology developed by the research team of Jilin University is different from the internationally used "passive pressure maintaining and thermal insulation sampling" drilling principle. The new technology first proposes the "active cooling and freezing sampling" principle, and invents the drilling mud enhanced refrigeration method, hydrate bottom quick freezing sampling method and high-temperature pulse thermal stimulation mining technology[25]. The main technical indexes are higher than the similar technologies abroad.

4.6. Comprehensive method
By using the methods mentioned above, the advantages are complementary, so as to achieve the purpose of mining combustible ice. Such as electric heating assisted depressurization, CO2 replacement assisted depressurization.

5. Conclusions
As a new energy with huge reserves, combustible ice is not only widely distributed, but also environmentally friendly. If commercial exploitation can be realized, the world energy crisis will be effectively alleviated. However, the current mining technology still cannot meet the requirements of commercial mining, which needs to be further solved in mining technology and environmental protection.

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