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Polar Offshore Engineering Equipment: Development Status and Key Technologies

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Abstract: Polar offshore engineering equipment provides a major platform and symbolizes the strength of China to participate in Arctic offshore oil and gas development. Currently, the design, construction, and support capacities of China’s polar offshore engineering equipment are not internationally recognized, despite the large shipbuilding sector of China. In this article, we analyze the development demand for polar offshore engineering equipment in China, present the application status of these equipment, investigate the key technologies, and summarize the existing problems regarding these equipment in China. Furthermore, we propose the establishment of a research and application innovation project of common key technologies for Arctic offshore oil and gas exploration and development, an international research and development center for polar offshore oil and gas engineering technologies, and a China–Russia Arctic energy joint venture company. This study is centered on the coordination of the Arctic development and environmental protection capabilities, and aims to provide a reference for developing polar offshore engineering equipment in China and provide guidance for China’s participation in Arctic oil and gas development.
Keywords: Arctic oil and gas; low temperature; sea ice; vulnerable ecology; offshore engineering equipment

1 Introduction

The Arctic has a severe natural environment that poses several challenges, such as low temperature, sea ice obstruction, iceberg encounters, snowstorms, fragile ecological environment, polar night disturbance, and poor visibility, which result in strict requirements for polar offshore engineering equipment. The Arctic is rich in oil and gas resources. According to the 2008 United States Geological Survey assessment report, the Artic has oil reserves to be discovered with a capacity of 90 billion barrels and 47 trillion m^3 of natural gas, accounting for 13% and 30% of the world reserves, respectively. Russia has the largest reserves in the world, accounting for approximately 58%, most of which are natural gas resources [1]. In this paper, the polar offshore engineering equipment used for Arctic offshore oil and gas development is analyzed.

With the melting of Arctic sea ice, the volume of freight transportation in the Northeast channel has increased, and the value of the golden waterway has gradually reflected this increase. The navigation window time is generally from early July to the end of September, but PC4 ice class or above can be used to navigate the Northeast channel throughout the year [2]. It means that the technical difficulty of oil and gas exploitation and transportation in the

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Arctic has been reduced. Due to the high risk of oil and gas development in the Arctic, the main approach to reduce costs and ensure safety is to rely on high-technology polar offshore engineering equipment. According to statistics, more than 50% of the Arctic oil and gas development investment in 2012–2018 was used for oil pipeline construction, 31% was used for offshore platform construction, of which 75% represented investment on fixed platforms [3]. In the past decade, there were several oil and gas projects in Arctic, such as Terra Nova and White Rose in Canada Newfoundland, SnØhvit and Goliat in Norway, and Sakhalin II and Yamal liquefied natural gas (LNG) projects in Russia [4].

At present, Russia is the main promoter of oil and gas development in the Arctic, whose national strategy considers the Arctic as an energy strategic base. By revising policy regulations, Russia will reduce the tax rate of oil and gas development in the Arctic, increase the proportion of foreign investment, and attract foreign investment and technical services. Russian companies, such as Novatek, Gazprom, and Rosneft, as well as oil and gas companies from non-Arctic countries such as France Total, Italy Eni, and UK shell, are rushing to enter the Arctic Ocean [5]. Since 2014, European and American sanctions on Russia oil industry have been extended to the signed cooperation projects, including restricting investment or providing equipment/technology exports [6]. Russia expects other countries, such as China, to participate in the development of Arctic oil and gas resources, including financial investment, oil and gas exploration, equipment manufacturing, and energy transportation.

China is an important country in world trade, energy import, and shipbuilding sectors. Participating in the development of Arctic oil and gas resources is helpful to China's economic development, energy supply, and offshore equipment export. However, the participation of China is still in small scale because of factors such as the weak capacity of its polar offshore engineering equipment and some key technologies that need to be developed. Based on energy supply and equipment export, this paper analyzes the development demand of China polar offshore engineering equipment, studies the overall application status of polar offshore engineering equipment considering the overall oil and gas development, and summarizes the key technologies of oil and gas equipment in the Arctic. Finally, several suggestions on the development of China polar offshore engineering equipment are provided as a reference direction for the country and related industries to participate in the Arctic oil and gas development.

2 Development demand of polar offshore engineering equipment in China

2.1 Promoting offshore oil and gas exploitation in the Arctic and building a stable channel for energy import from the Arctic

The political environment in the Arctic is stable and the sea routes are short. China's future economic and social development will result in an increasing demand of oil and gas imports. The establishment of multiple energy supply channels is an important measure to ensure China's energy security. In this regard, there is a significant demand for the rich and clean oil and gas resources in the Arctic. With the increase of oil and gas development in the Arctic, the Polar Silk Road is expected to become one of the main energy import channels in China. To meet the rigid demand of China's social and economic development for energy import growth, it is important to develop polar oil and gas offshore equipment, participate in the Arctic oil and gas development through equipment export, engineering services, and financial investment, and provide equipment support for low price competition for Arctic oil and gas import share.

2.2 Reducing the implementation risk of Arctic oil and gas projects and maintaining the security of China's Arctic oil and gas investment

China has supported Russia Arctic oil and gas development. From 2013 to 2016, China acquired 29.9% of the Russian Arctic Yamal LNG project, provided bank loans totaling 12 billion US dollars, and participated in offshore equipment construction, oil and gas field engineering services, and ports construction. In 2019, China National Petroleum Corporation and China National Offshore Oil Corporation (CNOOC) acquired 10% of the shares of Russian Arctic LNG-2 project. In the future, the Arctic LNG-3~LNG-7 project will still be an important direction for China's overseas investment. At present, the volume of direct investment of China in the Arctic is more than 30 billion US dollars, and the huge investment risk cannot be neglected. Unfavorable oil and gas exploration, oil and gas leakage accidents, equipment construction delay and other factors lead to project delay or even failure. To safeguard China's overseas investment security and investment income, it is important to develop polar oil and gas offshore equipment technology, overcome the constraints of the Arctic severe natural environment, and enhance the

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technical strength to participate in Russia Arctic oil and gas development based on the improvement of the industrial and science & technology systems of China.

2.3 Promoting the development of polar emerging industries to enhance maritime power

The offshore equipment for Arctic oil and gas development has a considerable value. Taking the LNG-2 project in the Arctic as an example, the total order price of the new gravity concrete platform, ice breaking LNG carrier, ice breaking oil tanker, and other equipment in the project exceeds 12 billion US dollars. According to preliminary statistics, more than 10 Arctic oil and gas projects are planned to be developed. Future orders of Arctic oil and gas offshore equipment are estimated to exceed hundreds of billions of dollars, providing a huge market for the development of the shipbuilding industry. The development of polar oil and gas offshore equipment for China's long-term economic and social development is considerably important. Key technologies should be developed, such as cold insulation, ice breaking and deicing, frozen soil drilling, and underwater communication and navigation.

2.4 Accumulating Arctic data and operational experience to enhance scientific understanding of the Arctic environment

The participation of China in the development of Arctic oil and gas resources has several benefits, such as driving equipment technology and professional teams to enter the Arctic, making use of the Arctic operation activities to strengthen the investigation on the Arctic environment and resources, comprehensively understanding the distribution of Arctic geology, hydrology, and acoustic and electromagnetic fields, enhancing China's scientific knowledge of the Arctic, and conducting field evaluation of domestic polar oil and gas offshore equipment. The accumulation of experience in the Arctic sea and seabed operations will enhance the capabilities in Arctic emergency rescue and international governance.

3 Application status of polar offshore engineering equipment

Among the countries around the Arctic, Russia has the largest and most active Arctic oil and gas reserves [7], Norway has rich experience in Arctic oil and gas exploitation technology [8], the United States and Canada have uncertainties in Arctic oil and gas exploitation, and Greenland and Iceland have predicted reserves but no actual exploitation. In the future, Russia, Norway, Iceland, and Denmark will be potential partners for China to participate in the development of polar resources in the future. Among them, Russia is the largest partner, and the increase of energy trade between China and Russia in the future will mainly come from the Arctic sea.

3.1 Arctic oil and gas exploration equipment

The equipment suitable for offshore oil and gas exploration in the Arctic is very limited. Anti-ice drilling ships and anti-ice semi-submersible drilling platforms are mainly used. The conceptual design of a circular drilling platform has been developed, which can work in the Arctic all year round. The main design factors of Arctic oil and gas exploration offshore equipment include sea ice, wave, water depth, weather, and operation time. The key systems are drilling equipment, sea ice control system, positioning system, lifting system, and underwater equipment.

Polar drilling ships have a large deck area, strong self-sufficiency, and flexibility. In 2007, the United Kingdom Stena drilling company commissioned South Korea Samsung Heavy Industries to build the world's first polar deep-water drilling ship, Drillmax ICE IV, at a cost of 1.15 billion US dollars, equivalent to two to three times the cost of conventional drilling ships. The main characteristics of the ship are 228 m in length, 97000 tons in displacement, –40 °C design temperature, PC5 ice class, 3000 m in design operating water depth, 10000 m in maximum drilling depth, DP3 dynamic positioning, resisting 16-m waves and 41-m/s sea breeze.

Polar semi-submersible drilling platforms are suitable for deep water and low ice condition areas. The polar semi-submersible drilling platforms built in 2001–2019 are shown in Table 1. COSL prospector is the fourth deep-water semi-submersible drilling platform built by CIMC Raffles for CNOOC in 2014. The platform is 104.5-m long, 70.5-m wide, 37.55-m high, with a maximum working depth of 1500 m and a maximum drilling depth of 7600 m. It meets the requirements of ice class, environmental protection, and low temperature operation, and can operate in the severe environment of the North Sea in Norway. In 2015, CIMC Raffles built the polar semi-submersible drilling platform "Viking Dragon" for Norway, the first deep-water semi-submersible drilling platform suitable for operation in Arctic waters built in China. The maximum working water depth of the platform is 500 m, which can be upgraded to 1200 m, and the maximum drilling depth is 8000 m. The platform is equipped with DP3 dynamic positioning system and

8-point mooring system, and the minimum service temperature is –20 ℃, which can meet the demand of the ice class.

Table 1. Polar semi-submersible drilling platforms built in 2001–2019.

Name of vessel	Year	Country	Length (m)	Max drilling depth (m)
Leiv Eiriksson	2001	China	119	9100
West Phoenix	2008	South Korea	83	9100
Transocean Spitsbergen	2009	Norway	120	9100
Polyarnaya Zvezda	2010	Russia	122	7500
Severnoye Siyaniye	2011	Russia	126	7500
Scarabeo 8	2011	Italy	119	10 600
COSL Prospector	2014	China	105	7600
Songa Encourage	2015	South Korea	116	8500
North Dragon	2015	China	107	8000
Songa Enabler	2016	South Korea	116	8500
Hai Yang Shi You 982	2018	China	105	9100
Beacon Pacific	2019	China	107	8000

3.2 Arctic oil and gas development equipment

There are four types of offshore oil and gas exploitation modes in the Arctic: onshore–offshore oil exploitation, fixed platforms, floating platforms, and subsea exploitation, as shown in Table 2. Arctic offshore oil and gas development equipment includes artificial islands, concrete gravity platforms, floating production storage and offloading (FPSO) units, floating platforms, and underwater production systems [9].

Table 2. Arctic offshore oil and gas production modes.

Main mode	Equipment type
Onshore	Onshore production of offshore oil, such as Sakhalin gas field in Russia
Fixed type	Artificial island + seabed pipeline, such as Northstar project
	Concrete gravity platform + shuttle tanker or seabed pipeline, such as PA-B project in Russia
	Jacket platform + seabed pipeline, such as Cook Bay area in the United States
Floating	FPSO + Subsea system, such as Goliat project in Norway
	Floating platform + seabed pipeline, such as Aasta Hansteen in Norway
Seabed	Subsea production system + land terminal, such as Norway SnØhvit

Artificial islands are mainly used in the Arctic offshore areas of the United States, Canada, and Russia, and belong to the cross field of marine engineering and civil engineering. The key technologies include ice area reclamation, frozen soil construction, and slope stability.

Concrete gravity platforms are the most widely used production platforms in the Arctic, and are mainly suitable for shallow water (water depth < 100 m). Typical examples are Hibernia platform, Prirazlomnoye platform, and Arctic LNG-2 platform. Their critical structures are caisson, column, and upper deck. The advantages are that the lower caisson is used for oil storage, the platform is stable by its own weight, and it has stronger resistance to sea ice environment load and corrosion.

FPSO units are used in the area where the Arctic ice situation is not very serious. Their advantages are strong wind wave resistance, wide range of water depth, large oil storage/unloading capacity, mobility, and reusability. However, it is considerably affected by environmental loads such as waves and sea ice. FPSO units are used in four active projects in the Arctic: Terra Nova and White Rose in the eastern waters of Newfoundland, Balder oilfield in the Norwegian Sea, and Goliat oilfield in the Barents Sea of Norway.

Subsea production systems have become the main method for deep-water oil and gas exploitation. Their critical equipment include subsea wellhead, Christmas tree, subsea manifold, jumper, subsea pipeline, and riser system. To prevent sea ice damage, the key technologies are that underwater wellhead and manifold are lower than seabed, weak connection technology is adopted between pipeline and equipment, and buried depth of pipeline is large. Norway SnØhvit project is the first offshore gas field developed with a full subsea system, with offshore distance of 145 km and water depth of 250–345 m. It was put into operation in 2007.

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3.3 Arctic oil and gas transportation equipment

Offshore oil pipelines can be connected in series with offshore production platforms and onshore facilities, offshore platforms in the Arctic, underwater well heads and production platforms, production platforms and nearby floating bodies, underwater well heads, and onshore facilities. Subsea pipelines are the “blood vessels” of oil and gas production, which connect subsea well heads and subsea production facilities in series and are used to reduce the number of platforms required by distributed oilfield.

The shipping cost of oil and gas resources is considerably lower than that of seabed pipeline, and the transportation scope is more flexible. The design of polar LNG carriers should consider the rapidity and seaworthiness under normal sea conditions, and the two-way ice breaking performance under ice sea conditions; the Azipod electric propulsion system is usually adopted. The LNG cabin is mainly spherical and membrane-type. In November 2016, the world first dedicated Arctic LNG carrier, Christophede Margerie, was successfully completed, with PC4 ice class and continuous ice breaking thickness of 2.1 m. The new cost was 330 million US dollars, about twice the cost of conventional LNG carriers.

3.4 Arctic oil and gas operation support equipment

Logistic support is very important for the drilling operation in the Arctic region, and polar supply ships are the key to ensure logistic support. Due to the short drilling time and high drilling cost, it is necessary to ensure the continuous supply of drilling equipment materials to maintain the continuous drilling operation. A representative polar supply ship is ARC105 ice breaking platform supply ship developed by Aker Arctic technology company, which is mainly used to provide materials and equipment for offshore platforms and drilling ships, conduct ice breaking/ice area management operations, and owing to its fire prevention and rescue capabilities, provide rescue and guarding services for offshore structures.

In summary, the semi-submersible platforms are mainly used for oil and gas exploration in the Arctic, and new drilling vessels with oil storage function will be the development direction in the future. Artificial islands and gravity platforms are mainly used for Arctic oil and gas production. In the future, with the development of deep sea, FPSO units, Spar platforms, and underwater production systems will be the mainstream methods. Considering the long distance of logistics support in the Arctic, platforms with drilling and production functions will be welcomed by the market. As the cost of using seabed pipelines for oil and gas transportation in the Arctic is too high, ice breaking tankers/LNG carriers will be the main force in the future. Polar offshore engineering equipment have special requirements in ice resistance, sea ice management, emergency escape, fire escape, self-sufficiency, and environmental protection.

4 Key technologies of polar offshore engineering equipment

4.1 Arctic sea ice environment prediction and ice management system

There are permanent ice sheet, first-year ice, large-area floating ice, and large icebergs in the Arctic Ocean. Research on sea ice environment is a prerequisite for the design, construction, and operation of polar offshore engineering equipment. The Arctic sea ice poses many challenges to the structure design, such as the load of sea ice on the structure, safety assessment of iceberg collision, and navigation performance assessment in a mixture of ice and water. The sea ice monitoring system for a specific operation area should be researched and developed. The key technologies include: sea ice distribution, sea ice drift monitoring, ship-based sea ice mechanical property acquisition system, shipborne radar ice detection, underwater environment detection technology, high-precision sea ice prediction model, and accurate prediction of sea ice threat.

To achieve long effective operation time, Arctic offshore structures should be assisted by a sea ice management system in addition to improving anti-ice collision capability. The sea ice management system refers to the general marine activities to avoid collisions between floating ice/icebergs and offshore platforms, including sea ice monitoring and forecasting, ice movement warning, and ice breaking ship management. The ice warning system around the operation area should be studied and developed. An intelligent collaborative operation management system for several ice breakers should be established to improve the overall ice breaking efficiency of the fleet used to control sea ice and avoid damage to offshore equipment.

4.2 Basic design technology of polar offshore engineering equipment

The minimum temperature of Arctic waters in winter is lower than –50 ºC, and the maximum temperature in summer is generally lower than 5 ºC. The deck mechanical equipment and the piping system of polar offshore equipment are exposed to a low temperature environment, resulting in equipment freezing, piping freezing, and oil flow weakening. There is also ice on waves and low-temperature freezing rain for polar offshore equipment, which have a considerable impact on the stability of the platform and the safety of personnel in open-air activities. Focus should be given on low-energy deicing, intelligent deicing, cold insulation, energy saving, and other key technologies of low-temperature protection and energy comprehensive utilization, to meet the needs of long-term operation in low-temperature environments.

The offshore equipment operating/navigating in ice covered waters is often impacted and squeezed by icebergs and floating ice. The ship structure should have improved ice resistance ability to avoid sea ice damage. Owing to the needs of investigation, rescue, and other operations, polar offshore equipment requires a certain degree of ice breaking ability and propulsion ability to break through the continuous ice sheets. Key technologies, such as ice load prediction and structure design technology, ice breaking technology with high-power propulsion, and ice breaking operation in the sea, should be developed to meet the anti-ice and ice breaking requirements of polar offshore equipment.

Arctic oil and gas operations provide special requirements for offshore equipment in terms of green environmental protection, cold protection and thermal insulation, and anti-ice breaking. Large-scale comprehensive functional platforms/ships with exploration, exploitation, storage, and oil and gas pretreatment are welcomed by the market. Ice breaking carriers with long-term navigation in Arctic waters have become the preferred equipment for polar development. Focusing on the demand of oil and gas development in the Arctic, studies on the overall design technology of new polar platforms and ships should be conducted, and key technologies, such as an integrated platform for exploitation, processing, and oil storage, design of a high ice-class ship, and design of a new ice breaking ship should be developed, such as to fill the blank area of polar offshore engineering equipment technology.

Test methods are the main means to evaluate the ice load. The evaluation of navigation, ice breaking, and positioning performances of new polar ships/platforms usually depends on the ice pool test. Different from the conventional pool test, the mechanical similarity condition of simulated ice should also be considered in the ice pool test. Owing to the differences in ice making processes and refrigeration system designs, the ice pool test method and similar extrapolation methods are also different. The ice pool test technology, such as polar sea ice simulation preparation and platform anti-ice performance test, should be developed.

4.3 Power and matching technology of polar offshore engineering equipment

The power plant of polar offshore equipment should adapt to the low temperature environment, remote areas, and sea ice conditions to avoid ship stagnation or being besieged by sea ice, which may lead to sea damage or pollution accidents. Diesel electric power systems are the mainstream systems for icebreakers in the world. Nuclear power is more conducive to ensure the propulsion, power supply, heating, and other needs of the ship. Dual fuel power represents a development tendency of green energy in the future. Focus should be given on the development of polar ocean LNG power, nuclear power, and pod thrusters to serve the needs of polar operations.

The polar ship/platform is affected by the combined action of ice, wind, waves, currents, and tide. Three methods, namely, pure dynamic positioning, mooring positioning, and combined positioning, can be adopted to support the smooth progress of offshore drilling and oil production. Large icebergs and large areas of floating ice endanger oil tankers and drilling platforms. Drilling platforms should be able to disconnect from oil wells at any time. Key technologies, such as polar mooring and dynamic positioning, joint control technology of mooring and dynamic positioning, and fast disconnection and reconnection of high load mooring, should be developed to meet the requirements of operation positioning.

Acoustic waves are an effective carrier for long-distance transmission of underwater information. Research and development (R&D) on underwater acoustic signal processing and sonar equipment is fundamental in the development of Arctic activities, such as underwater communication, navigation, positioning, and ocean environment and climate acoustic observation detection. By studying the physical characteristics of underwater acoustics and underwater acoustic technology, scientific problems such as recognition of acoustic field characteristics in polar environment, underwater acoustic network detection, and communication mechanism can be solved. This can enable the development of polar distributed long-term observation platforms, mobile underwater

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acoustic observation platforms, polar sub buoy and information ice penetrating communication systems, low-temperature sensors, underwater acoustic monitoring systems, and underwater acoustic communication systems to adapt to the polar environment. The long-distance underwater acoustic communication and networking under the ice should be realized to build the integrated ability of underwater detection, communication, and positioning.

The construction of polar ships cannot be separated from the development of low-temperature steel, which can adapt to the harsh polar environment. Low-temperature steel has high strength, corrosion resistance, low temperature crack arrest, easy welding performance, ice water corrosion resistance, etc. The polar ecological environment is fragile, and the environmental protection of coating materials is strictly required. The hull should be coated with low friction coating resistant to ice wear, and the LNG process module should be coated with a special coating to prevent brittle fracture caused by –163 ºC LNG splashing on the steel structure. Focus should be given on the development of marine low-temperature high-strength steel, low-temperature vessel high-strength steel, low-temperature non-metallic sealing materials, anti-icing coating materials, lightweight thermal insulation and fireproof materials, low-temperature cable materials, and other low-temperature materials. The key technologies for achieving low-temperature resistance, corrosion resistance, wear resistance, easy welding, and high toughness should be developed.

4.4 Arctic offshore oil and gas drilling system and technology

Permafrost in the Arctic poses considerable difficulties to foundation construction and is the key problem of drilling in polar cold sea. Drilling in permafrost results in melting of the pore water in permafrost and collapse of the borehole; in addition, drilling increases the permafrost temperature and causes the decomposition of natural gas hydrate, resulting in gas invasion. In severe cases, it can lead to kick or blowout. Focus should be given on the development of drilling bit, drilling fluid, cementing slurry, and other products suitable for drilling in frozen soil, and research on special technologies and equipment such as low temperature gas drilling, casing drilling, and thermal insulation casing is required.

To expand the production area of platforms or artificial islands, extended reach wells are needed for oil and gas development in the Arctic. At present, the horizontal displacement record of extended reach wells has exceeded 10 km. The technical problems such as guide design, trajectory control, and friction reduction should be solved.

The time window suitable for offshore drilling in the Arctic is from early August to early October every year. In this period, the maximum wave height is more than 10 m. The construction environment in the sea area is complex, with strong waves, low temperature, heavy fog, and complex formation, which poses considerable risks to drilling operations. The risk analysis method is mainly used to identify the probability level of each risk point, formulate feasible preparation schemes, and control the safety level of Arctic oil and gas drilling in real time.

4.5 Subsea system and technology of oil and gas in the Arctic Ocean

The Arctic subsea system includes subsea wellhead, Christmas tree, subsea manifold, seabed pipeline, and riser system. To prevent sea ice from causing damages to the system, the Arctic subsea wellhead and manifold should be lower than the seabed, a weak connection technology can be adopted between the pipeline and equipment, and the gathering and transportation pipeline is deeply buried or covered with gravel/soil for protection. In view of the Arctic low temperature, sea ice, and other special ocean environment conditions, studies on the basic design technology of Arctic seabed pipeline, riser, and underwater production systems have been conducted. The key technologies include underwater control and communication technology, underwater long-distance power supply technology, underwater oil and gas gathering and transportation technology, and overall design of underwater pipeline, such as to meet the requirements of high pressure resistance, high corrosion resistance, and large displacement of oil and gas production.

To expand the range of polar operation depth, underwater vehicles are an important development direction. Underwater vehicles can be operated on board/on shore to realize the detection, mapping, target identification, sampling, and other works of several hundred meters under the ice. They can also be used to lay underwater communication systems and install underwater modules. The R&D of underwater drilling robots, remotely operated vehicles, and manned submersibles can ensure the advantages of underwater activities in the Arctic.

4.6 Rescue technology for oil and gas accidents in the Arctic Ocean

Marine accidents occasionally happen in the Arctic, which lead to fuel leakage and damages to the fragile ecological environment of the Arctic. In March 1989, the oil tanker “Exxon Valdez” of the United States hit a reef near the north pole of Alaska, releasing 8 million gallons of crude oil. In December 2012, the Shell Group’s “KULLUK” was towed to the Gulf of Alaska, and the towline broke. Then, the ship ran aground and the fuel leaked.

For oil spills in ice area, focus should be given on the research of acoustic electromagnetic detection technology, reclamation and recovery technology, overall plan for emergency rescue, and plugging of blowout under ice, to improve the ability of oil spill accident prevention and emergency response.

Under extremely cold conditions, the fire escape technology of offshore equipment is challenging. Arctic offshore equipment generally adopts closed thermal insulation design. Equipment and facilities, which are flammable and explosive, are installed indoors; this considerably increases the risk of combustion and explosion. Staff wearing heavy protective clothing and ice on the surface of offshore equipment result in difficult evacuation. Arctic maritime rescue relies on professional rescue equipment such as icebreakers and helicopters. The change of sea ice and complex weather increase the difficulty of rescue. Focus should be given on the research of Arctic sea escape, evacuation and rescue technologies, life-saving equipment, and emergency rescue logistics support, to enhance the ability of Arctic sea life safety rescue.

4.7 Green environmental protection technology of polar offshore engineering equipment

To protect the polar ocean environment, the mandatory *Polar Rules* proposed by the International Maritime Organization (IMO) came into effect on January 1, 2017. Their requirements are stricter than those of the SOLAS Convention and MARPOL convention. The *Polar Rules* prohibit or strictly restrict the discharge of oil, chemicals, domestic sewage, garbage, food waste, and other substances. Arctic countries should strictly limit the environmental pollution caused by oil and gas operations. Russia indicates that cuttings, mud, domestic sewage, oil sewage, and garbage formed during oil and gas drilling operations cannot be directly discharged into the sea. They are usually transported by tugboat to land for treatment to avoid pollution and damage to the ocean environment. The major impact of black carbon on the environment is its greenhouse effect, particularly on the melting of polar glaciers. Canada, Germany, Finland and other countries have conducted studies on measurement methods, influencing factors, and emission reduction technologies, and proposed that IMO should formulate control measures for polar black carbon emissions, which directly impacts the design of main engines of ships and emission reduction control technologies. Key technologies, such as oil and gas operation wastewater treatment and black carbon emission control, should be developed to meet the needs of green environmental protection in Arctic operation, proposals in line with China's interests should be elaborated, and China should actively participate in the formulation of international rules.

Polar ships/platforms consume considerable energy during operation. By reducing ship resistance, improving propulsion efficiency, effective operation, and control, and introducing clean energy, polar ships can reduce energy consumption, such as to improve ship operation, reduce costs, and reduce gas emissions generated by polar ship operation. The polar green energy power, low-temperature endurance of batteries, and fast charging system should be developed to meet the green energy demand of long-term ice operation equipment.

5 Existing problems of polar offshore engineering equipment

5.1 Existing problems

5.1.1 R&D ability of China's polar oil and gas offshore equipment is deficient

China has a certain foundation in the technology and equipment for the field of polar offshore oil and gas exploration and development, such as the Arctic Barents Sea summer ice free/less ice exploration experience, Arctic LNG core module construction experience, and Arctic northeast channel transportation experience, from which the R&D of Arctic offshore oil and gas technology and equipment started. However, China's R&D of oil and gas technology and equipment in the Arctic is still very deficient, and the number of independent core technologies and equipment is very limited. In particular, the basic design of polar offshore equipment has not been developed, and polar drilling ships, polar gravity platforms, polar LNG ships, and other equipment are all undeveloped areas of design and construction.

5.1.2 China has limited experience in oil and gas engineering in the Arctic

The operation of oil and gas fields in China ice area is mainly concentrated in Bohai Bay area in winter, and the ice thickness is less than 90 cm. Compared with Bohai Bay, the Arctic ice thickness, operation window period, and logistics support are significantly different; thus, it is difficult for Bohai Bay oil and gas equipment technology to be directly applied to the Arctic region. Due to the lack of sufficient technical reserves, China does not have the overall contracting capacity for Arctic oil and gas projects, as well as for Arctic project bidding, design, and construction, which hinders its participation in the Arctic oil and gas cooperation.

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5.1.3 China oil and gas cooperation projects in the Arctic are very limited

Due to European and American sanctions, some investment, equipment, and technology had to be withdrawn from Russia Arctic oil and gas projects. With the advantages of offshore equipment manufacturing and the demand of oil and gas consumption market, this is the right time for China to enter Arctic oil and gas projects. However, China's international oil and gas cooperation projects in the Arctic are very limited, and the actual Arctic oil and gas exploration areas are limited to individual blocks in Barents Sea and Kara Sea. China has not yet obtained the data about the distribution of Arctic oil and gas reserves, and cannot accurately assess the feasibility of the Arctic project. There is only one Yamal actual participation in Arctic oil and gas development; in addition, China attempts to participate in the Arctic LNG-2 project. Only the change from a participant of the Arctic oil and gas project to an actual operator can provide the decision-making power of the Arctic oil and gas development to China. Then, more domestic equipment products and technical services can be applied in the Arctic to ensure China's safe and stable access to the Arctic oil and gas strategic resources.

5.1.4 China's scientific research support for Arctic oil and gas exploration and development is deficient

The white paper *China Arctic Policy* indicates that enterprises are supported to participate in the development of Arctic oil, gas, and mineral resources through various forms of cooperation on the premise of protecting the Arctic ecological environment, such as to promote oil and gas drilling and production in the Arctic waters. The exploration, evaluation, exploitation, transportation, and engineering implementation of Arctic offshore oil and gas resources rely on the technical support of high-end polar offshore equipment. Since 2012, the Ministry of Industry and Information Technology and the Ministry of Science and Technology have supported the R&D of key technologies for polar ships, polar submersibles, polar environment detection, and also basic generic technologies. However, a series of problems, such as high-precision exploration of Arctic offshore oil and gas resources, engineering geological survey, project risk assessment, overall project design, sea ice control and management, and under-ice operation and exploitation, have not been solved. It is difficult to achieve a new situation of Arctic offshore oil and gas development cooperation in the short term only by the R&D input from the enterprises.

5.2 Key technology development points

5.2.1 R&D of polar ocean key basic materials

These materials include high-strength steel for low-temperature use, high-strength steel for low-temperature containers, low-temperature non-metallic sealing materials, anti-icing coating materials, lightweight thermal insulation and fire-proof materials, and low-temperature cable materials. The key technologies should be developed regarding low-temperature resistance, corrosion resistance, wear resistance, easy welding, and high toughness to meet the needs of polar special environmental engineering equipment.

5.2.2 R&D of polar ocean green-energy power equipment

Research should be conducted on high-power propulsion technologies, such as polar ocean LNG power, nuclear power, and full rotation propeller, as well as low-temperature endurance and fast charging systems for batteries, to meet the green energy demand of long-term ice operation equipment. Moreover, research should be conducted on low temperature resistance reliability of polar mechanical equipment. Low energy consumption, anti-freezing, and large area deicing technologies should be developed to improve adaptability of offshore equipment to low-temperature environments.

5.2.3 R&D of basic common technology of polar offshore equipment

Research should be conducted on key technologies such as overall performance of polar ships, ice load prediction, structural safety assessment, new ice breaking technology, cold protection and antifreeze, and low-temperature lubrication and sealing. The R&D level of high ice class ships should be enhanced to drive the development of heavy ice breaking ships, polar LNG ships, polar oil tankers, and other key ship types. The large-scale ship model technology in the ice pool test should be studied to improve the simulation ability of complex sea ice conditions, test the ice breaking performance of new ships, ice navigation performance, and anchor mooring positioning performance, and verify the adaptability of offshore equipment to low temperature environments.

5.2.4 R&D of polar oil and gas resources exploration and development equipment

The R&D of polar geophysical exploration ships, polar drilling ships, polar gravity platforms, and polar floating oil storage ships should be conducted to improve the design level of polar offshore equipment, and increase the international market competitiveness of shipbuilding industries. The R&D of polar underwater production systems and underwater vehicles should be conducted to develop large-diameter low-temperature oil and gas valves, low-temperature test and inspection, ice breaking operations, underwater detection, and other key technologies. The R&D of polar oil and gas drilling equipment should be conducted to develop polar frozen soil drilling, cementing, and hydraulic fracturing technologies to increase the technical service capacity for polar cold sea drilling and completion operation. The R&D of sea ice control systems, oil spill warning systems, and oil spill rescue equipment should be conducted to develop key technologies such as sea ice monitoring and forecasting, sea ice interception and breaking, polar oil spill prevention, polar oil spill treatment, and establish polar oil and gas leakage accident prevention and emergency treatment capacity.

6 Suggestions on the development of polar offshore engineering equipment in China

6.1 Understanding the window period of Sino Russian Arctic oil and gas cooperation and accelerating the development of polar offshore engineering equipment

Under the initiative of the Polar Silk Road, the Arctic oil and gas cooperation should be taken as the starting point. The strategic opportunity of China participation in Russia Arctic oil and gas development should be grasped. The polar offshore engineering equipment should be taken as the basis and condition for technical service capacity, to achieve the binding of equipment and technology, enhance the breadth and depth of China’s participation, and promote the establishment of Arctic energy import channels.

6.2 Establishing a special project “Research and Application of Common Key Technologies for Arctic Offshore Oil and Gas Exploration and Development”

The Arctic LNG-2 project can be considered as an opportunity to solve a series of problems faced by the design, construction, and application of Arctic offshore oil and gas equipment. Focus should be given on polar ocean key basic materials, polar ocean green energy power equipment, basic common technology of polar offshore equipment, and polar oil and gas resources exploration and development equipment. Then, the equipment and technology system of Arctic oil and gas development in China should be developed. The participation in the Sino Russian oil and gas cooperation and development in the Arctic will become more significant.

6.3 Establishing an international R&D center for polar offshore oil and gas engineering technology with China and Russia as the main body and multi-party participation

The oil companies of Arctic offshore oil and gas development of China and Russia should lead engineering design companies, production and construction enterprises, colleges and universities, and other advantageous resources to form a stable R&D team of polar offshore oil and gas equipment, which will conduct long-term sustainable scientific research, open up the transformation channel of scientific research achievements of production, and provide an effective accumulation of cutting-edge technology and new products. The center will develop the core technology of equipment and system in the entire industrial chain, promote the localization of key equipment and components, organize international cooperation such as achievement display, technical training, and personnel exchange, and promote the deep integration of equipment R&D and application cooperation between China and Russia.

6.4 Establishing a Sino Russian Arctic energy joint company to promote solid cooperation on the Polar Silk Road

The Sino Russian Arctic energy joint company should be established, as well as the cooperation in specific oil and gas blocks. The participation of China in Arctic offshore oil and gas development should be considered as a partnership, and China as a partner and shareholder. More China equipment can be used in Arctic offshore oil and gas exploration and development in an all-round manner. At the same time, the service capabilities of oil and gas development equipment in communication and navigation should be enhanced to promote the interconnection along the Polar Silk Road and provide more economic solutions for the infrastructure construction of Northeast Arctic routes.

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