DOI 10.15302/J-SSCAE-2020.06.001

Deep-Sea Mining Equipment in China: Current Status and Prospect

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Abstract: The seafloor contains abundant mineral resources with rich variety, vast reserves, high grades, and great development and utilization prospects. Countries worldwide are accelerating the development of deep-sea mining equipment. This study analyzes the development status of deep-sea mining equipment in China and other countries and investigates deficiencies in technologies and equipment in China from the perspectives of fundamental scientific research, key technology development, and sea trial verification. Moreover, it summarizes the key scientific and technological issues to be resolved, and describes developing trends in deep-sea heavy operation equipment, ore transport equipment, and sea surface support vessels. We propose that deep-sea mining should adhere to the concepts of heavy equipment, collaboration, intelligence, and green development, and key technology innovation and independent research and development of mining equipment should be promoted. Demonstration projects should be developed for deep-sea polymetallic nodule mining to accelerate the development of deep-sea mining technologies and equipment, thereby realizing large-scale sea trials, conducting system design for long-term operations, and promoting commercial seabed mining.
Keywords: seabed mineral; deep-sea mining; deep-sea heavy operation equipment; ore transport equipment; sea surface support vessel

1 Introduction

There are abundant mineral resources on the ocean seabed. Proven deep-sea mineral resources with promising prospects include manganese nodules (MN), cobalt-rich crusts (CRC), and seafloor massive sulfides (SMS). Metal reserves such as manganese, nickel, and cobalt are much higher in the sea than on land. After achieving safe and efficient commercial mining systems and controlling the operational impact on the marine ecological environment, the abundant marine minerals will become a substitute for land-based sources and meet the requirements of economic development in the future [1]. Therefore, countries worldwide are accelerating the exploration and exploitation of marine mineral resources.

Research on deep-sea mining systems began in the late 1950s. The United States, Europe, Japan, and other countries proposed exploration and commercial exploitation schemes for mining MN [2,3]. Meanwhile, investigations in mining CRC and SMS were preliminarily considered. In the 1980s and 1990s, South Korea, India, and China joined the deep-sea mining research efforts to design mining schemes and propose commercial seabed mining projects [4]. In recent years, countries around the world have performed individual and integrated sea trials, resulting in the rapid development of deep-sea mining technology and equipment.

Despite the vast amount and high grade of mineral reserves available on the seabed, deep-sea mining is extremely difficult. The complicated terrain of the seabed, extremely high pressure, dark seafloor, and complex marine environmental conditions such as waves, ocean currents, and internal waves necessitate high-level safety requirements for the mining equipment. Multi-system cooperative control and joint operations during deep-sea

Received date: October 20, 2020; **Revised date:** November 15, 2020
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Funding program: CAE Advisory Project “Research on Development Strategy of Marine Equipment” (2020-ZD-02)
Chinese version: Strategic Study of CAE 2020, 22 (6): 001–009
Cited item: Yang Jianmin et al. Deep-Sea Mining Equipment in China: Current Status and Prospect. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2020.06.001

mining are highly difficult [5]. In addition, it is necessary to thoroughly evaluate the impact of deep-sea mining on the environment and propose appropriate environmental protection plans. As such, no comprehensive commercial deep-sea mining project has presently been executed in the world.

Following the demand for seabed resources for China's rapid economic development and to fulfill the strategic requirements of becoming a maritime power, exploration and exploitation of deep-sea mineral resources is imminent. Since the late 1980s, China has been conducting research on deep-sea mining technology and equipment, focusing on deep-sea mining systems including seabed mining equipment, pump-pipe lifting equipment, and sea surface support equipment. So far, system design and equipment construction capabilities for deep-sea MN mining have been preliminarily acquired. Additionally, investigations in the technology and equipment for the exploitation of CRC and SMS have also been conducted [6].

Although China has conducted a series of sea trials, a gap still exists between China and the developed countries in terms of system design and research capability, collaborative operation technology, and key technical equipment development. To date, China has not conducted any joint sea trial for a comprehensive deep-sea mining system; the key technologies have not been effectively verified; the R&D capacity of the core equipment and the stability and reliability of the system have not been improved; and conducting large-scale field tests still poses difficulties. Additionally, there are shortcomings in the design and manufacture of underwater core components, sensors, and materials, most of which are still imported.

To sum up, mining technology and equipment are significant issues in the research field of deep-sea development all over the world. Developed countries and regions such as the United States, Europe, and Japan have mastered the key technologies and acquired the key-equipment manufacturing capacity for deep-sea mining. Once the problem of impact on the seabed environment is solved, commercial exploitation is inevitable [6]. China is still in the initial stages of deep-sea mining development. Conducting demonstration projects, vigorously developing key technology and equipment, and accelerating the progress of large-scale field tests and commercial exploitation are urgently required to attain a favorable position in the development of international deep-sea mining.

2 Review of foreign deep-sea mining equipment

Four types of deep-sea mining systems have been proposed worldwide: drag bucket mining, continuous line bucket mining, automatic shuttle vessel mining, and pump-pipe lifting mining systems. Due to the low mining efficiency and serious damage to the environment, the first three mining methods have gradually faded out of research. Currently, research on deep-sea mining mainly focuses on the pump-pipe lifting method [7], which involves deep-sea heavy operation equipment, ore transport equipment, and sea surface support equipment.

In the 1970s, several international consortiums such as OMI successfully collected MN from the seabed in the Pacific Ocean at a depth of 5000 m [6]. Subsequently, Germany, Russia, Japan, South Korea, and India successively conducted sea trials to verify their technology and equipment [1]. In 2017, Japan completed a sea trial for collecting and transporting SMS at a depth of 1600 m [8], marking another step forward in the development of SMS mining. In recent years, the European Union has initiated projects such as "Blue Mining", "Blue Nodules", "¡VAMOS!" for the development of deep-sea mining [5]. Since 2017, the Netherlands and Belgium have successfully performed sea trials for the verification of deep-sea mining equipment and assessment of environmental impact. Deep-sea mining technology and equipment are gradually progressing. Table 1 summarizes the current status of sea trials and development of foreign deep-sea mining equipment. In summary, through a large number of sea trials, foreign countries have established relatively complete technical proposals for deep-sea mining, and have mastered the R&D capabilities of key technologies and equipment manufacturing, including safe operations and efficient collection using deep-sea heavy operation equipment, flow assurance of long-distance pump-pipe transportation, underwater power transmission, collaborative system control, underwater integrated navigation and positioning, and launch and recovery of deep-sea heavy operation equipment.

Owing to the inevitable effect on the seabed environment during deep-sea mining operations, the development of deep-sea mining technology and equipment will focus on solving environmental problems during operations, developing environment-friendly mining equipment, and reducing environmental impact by developing low-disturbance walking technology and efficient and accurate collecting technology in the future. Based on modern information technology, big data, artificial intelligence, and other technologies, deep-sea mining systems will further realize accurate operations, cooperative control, long-term operations and maintenance, and real-time control. High precision and intelligence are the main trends of future development.

DOI 10.15302/J-SSCAE-2020.06.001

Table 1. Review of foreign deep-sea mining trials and equipment development.

Year	Country/Institution	Water depth (m)	Trial items
1978	OMI	5500	Sea trial of MN collection
1978	OMA	4570	Sea trial of MN collection
1979	OMCO	5000	Sea trial of MN collection
1979	Germany/Preussag	2200	Sea trial of soft clay collection
1990	Russia/МГРИ	79	Sea trial for hydraulic lifting system
1996	India/NIOT & Germany/University of Siegen	500	Walking/collecting test for mining vehicle
1997	Japan/Polymetallic Nodule Mining System Research and Development Project	2200	Joint towing test for wire rope and mining vehicle
2002	Japan/JOGMEC	1600	Walking test for mining vehicle
2006	India/NIOT	450	Sea trial for mining vehicle
2009	South Korea/KIGAM	100	Sea trial for ore transport system
2012	Japan/JOGMEC	1600	Collecting test for mining vehicle
2013	South Korea/KIOST	1370	Sea trial for mining vehicle
2015	South Korea/KIOST & South Korea/KRISO	1200	Sea trial for hydraulic lifting system
2017	Japan/JOGMEC	1600	Collecting test for mining vehicle and hydraulic lifting test
2017	Belgium/DEME	4571	Sea trial for mining vehicles and assessment of environment
2017	Canada/Nautilus Minerals	—	Water test for mining vehicle
2017	EU/¡VAMOS!	—	Positioning, navigating, and perception test for mining vehicle
2018	The Netherlands/Royal IHC	300	Walking test for mining vehicle
2019	The Netherlands/Royal IHC	300	Walking test for mining vehicle

3 Status of deep-sea mining equipment in China

Deep-sea mining projects in China focus on the pump-pipe lifting system to exploit the deep-sea MN, while considering CRC and SMS. The main equipment includes deep-sea heavy operation equipment, ore transport equipment, and sea surface support equipment. Table 2 summarizes the main progress of deep-sea mining equipment in China. This section mainly expounds on the status of developing technology and equipment; the environmental issues in the development process will not be clarified in detail.

Table 2. Review of deep-sea mining equipment in China.

Year	Related institutions	Water depth (m)	Trial items
2001	China Ocean Mineral Resource R&D Association	135	Lake trial of mining vehicle
2016	Changsha Research Institute of Mining and Metallurgy	304	Sea trial of ore transport system
2018	Changsha Research Institute of Mining and Metallurgy	514	Sea trial of mining vehicle
2018	Changsha Research Institute of Mining and Metallurgy	2019	Large-scale CRC sampling vehicle
2019	Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences	2498	Sea trial of mining vehicle

3.1 Deep-sea heavy operation equipment

Heavy operations equipment for deep-sea mining includes ore mining, ore crushing, and ore collection equipment. Ore mining equipment is a core component of deep-sea mining, used mainly to strip bedrock or sediments from ore deposits, and performs cutting and tunneling functions. Different types of ore deposits require different mining equipment. Generally, MN are tiled on the flat seabed and coexist with seabed sediments. MN mining usually involves a hydraulic method, which involves collecting the ore through negative pressure suction using a high-pressure water jet around the nodules. As CRC grows on the surface of bedrock, it is generally stripped with a spiral drum mining device. SMS occurs near the seafloor hydrothermal area; the mining equipment requires both cutting and tunneling functions and, therefore, auxiliary cutting machines or multifunctional integrated mining equipment are generally used. The development of ore mining equipment in China is currently at the prototype design and test verification stage. Collecting tests have been conducted for MN and CRC in recent years. In July 2016, a deep-sea CRC mining vehicle developed by the Changsha Institute of Mining Research (CIMR) successfully conducted a mining test in the South China Sea, which verified the feasibility of using the spiral drum mining machine for mining CRC. In 2018, the CRC sampler developed by CIMR performed a sea trial. In 2018, the Institute of Deep-sea Science and Engineering of Chinese Academy of Sciences (IDSSE, CAS) conducted a large-scale sampler test of CRC, and verified the launch and recovery functions and seabed ore crushing in the South China Sea.

Ore crushing equipment is used for crushing and decomposition of large ores. In the process of seabed mining, ores must either be crushed owing to their large size or stripped from the bedrock. Therefore, the ore is usually mechanically crushed for collection. Generally, CRC and SMS have to be cut with spiral drum cutting or percussion drilling, whereas MN can be crushed with a crushing device installed in ore mining equipment. The CRC mining equipment available in China contains a cutting device, which has proven effective in sea trials. A few studies have been conducted on SMS crushing equipment. In 2018, IDSSE conducted a sea trial at a depth of 2500 m in the South China Sea, verifying the crushing and collecting abilities of CRC mining vehicles. In 2019, two CRC collecting tests were conducted in the South China Sea using a deep-sea CRC sampler. During the tests, the cutting thickness was automatically determined by the detecting the physical characteristics of CRC and the bedrock using a micro-topography-adaptive cutting–rushing–collecting integration device. The crushed CRC were then collected with a hydraulic water jet and transported to a buffer station.

Ore collection equipment is utilized to collect the crushed small pieces of ores to the ore storage tank or transport the particles to the sea surface support equipment through pipelines. Research on ore collection equipment in China has been performed earlier, and the preliminary test verification of ore collection equipment for MN and CRC has been completed. From 1991 to 1995, both hydraulic and hydraulic–mechanical mining methods were studied. In 2001, the China Ocean Mineral Resource R&D Association (COMRA), Changsha Research Institute of Mining and Metallurgy (CRIMM), CIMR, and other institutions completed a lake trial of the ore collection equipment and verified its feasibility in Fuxian Lake, Yunnan, at a water depth of 130 m. In 2018, the "Kunlong 500" mining vehicle developed by CRIMM completed a sea trial in the South China Sea at a depth of 500 m, verifying the adaptive hydraulic collecting function for MN. In 2018, a comprehensive sea trial for CRC mining was conducted successfully in China's deep-sea exclusive exploration area. A further sea trial of the CRC prototype mining vehicle was conducted in 2019, verifying the capacity of the hydraulic equipment for collecting crushed CRC.

In addition, deep-sea heavy operations equipment requires to be equipped with an underwater navigation and positioning system to support the mining tasks on the seabed. Several universities and institutions, such as Harbin Engineering University, Institute of Acoustics of Chinese Academy of Sciences, and China State Shipbuilding Corporation (CSSC), have conducted extensive research in the field of acoustic positioning technology. In 2004, China successfully developed the first underwater positioning and navigation system based on differential GPS. Under the 10th Five-Year Plan, a long-range ultra-short baseline positioning system was successfully developed. A deep-sea high-precision underwater integrated positioning system was successfully developed with the support of the National 863 Plan. In the sea trial of the "Kunlong 500" mining vehicle in 2018, the positioning accuracy of the mining vehicle reached 0.72 m at a depth of 500 m.

3.2 Ore transport equipment

Ore transport equipment, mainly used to transport the collected and crushed ores from the seabed to the sea surface, usually comprises a pump-pipe lifting equipment, underwater buffer station, and heave compensator.

The pump-pipe lifting equipment transports the ore–seawater mixture from the mining equipment to the sea surface at certain flow rates and concentrations. According to the operational environment of the deep-sea mining, the pump-pipe lifting equipment should overcome the influence of the complex marine environment, such as waves and currents, and is equipped with pressure resistance, corrosion resistance, wear resistance, and anti-clogging characteristics, as well as allows large particles to pass. Since the 1990s, COMRA, CRIMM, Central South

DOI 10.15302/J-SSCAE-2020.06.001

University, Minzu University of China, and Shanghai Jiao Tong University have been involved in relevant research on key technologies such as pump-pipe lifting equipment and long-distance pipeline transportation, and have achieved a series of milestones. Since the 8th Five-Year Plan, China has built a 30 m-high vertical pipeline lifting system to study the characteristics of pipeline transportation and the flow characteristics of submersible pumps [10]. During the 11th Five-Year Plan, a 224 m-high vertical pipe lifting test system was built to verify the rationality of the lifting process [6]. In 2016, a 300 m pump-pipe lifting system was tested in the South China Sea, with a 500 m^3/h slurry volume and 50 t/h ore transportation capacity.

An underwater buffer station is used to convert the ores collected with the mining equipment into a uniform ore-seawater mixture and transport it to the pump-pipe lifting equipment. Additionally, it helps in controlling the pipeline position and monitoring the sea conditions in the working areas. Research on underwater buffer stations remains at the design and test stages in China. Central South University has designed a water-jet-auxiliary buffer station that comprises a storage tank and a pump [11]. During the 13th Five-Year Plan, China Ship Scientific Research Center developed an underwater buffer station system for the impending sea trial, improving the independent design ability of China's deep-sea mining ore transport equipment [12].

The heave compensator is an important connecting device between the sea surface support vessel and pump-pipe lifting equipment and is installed on the top of the lifting pipe to suppress the motion of the pump-pipe lifting equipment that is caused by the motion of the sea surface support vessel in waves. The present heave compensator for deep-sea mining systems follows the heave compensator technology for offshore oil and gas platforms. Shanghai Zhenhua Port Machinery Company Limited, China University of Petroleum, Baoji Oilfield Machinery Corporation Limited, and Shanghai Marine Equipment Research Institute have conducted preliminary studies on heave compensation technology and made certain achievements. In 2017, Baoji Oilfield Machinery Corporation Limited manufactured the first prototype of a drill string heave compensator for sky vehicles in China, achieving a level similar to that of products in other countries in terms of performance indicators and safety measures, enhancing the independent supporting ability of deep-sea key equipment in China. During the 13th Five-Year Plan, Shanghai Marine Equipment Research Institute conducted further research on heave compensators for use in the impending sea trials of the National Key Research and Development Program of China.

3.3 Sea surface support equipment

The sea surface support equipment for deep-sea mining includes sea surface support vessels, cooperative control systems, positioning and navigation systems, ore preprocessing equipment, ore storage–transport equipment, and launch and recovery systems.

Sea surface support vessels are the surface centers of deep-sea mining operations, and provide functions such as collaborative system control, power supply, ore preprocessing, ore storage and exporting, as well as the launch and recovery of underwater equipment. In the early years, depending on the specific requirements of deep-sea mining activities, old cargo ships or drilling ships were upgraded into surface support vessels for sea trials. The surface support vessel commissioned in the approaching sea trial under the 13th Five-Year Plan was upgraded from an engineering vessel. At present, the only large-scale integrated mining ship in the world has been designed by a company in Singapore for Nautilus Minerals and built in the Mawei Shipyard in China. Although China gained a rich experience in the design and construction of large-scale special ships and deep-water offshore platforms, it is still insufficient for designing an integrated mining ship, owing to the complex integrated electric propulsion devices, moon pool structures, and ore preprocessing-storage-exporting facilities involved.

The cooperative control system establishes a central control system on the sea surface support vessel. It not only controls each piece of equipment in the system individually, but also enables the intelligent cooperative control of multiple facilities for joint operations to ensure launch and recovery, mining operations, and ore processing and transportation. In terms of individual equipment control, research on control systems for mining operations and launch and recovery activities has been conducted over the years. However, the control scheme for ore preprocessing and exporting has not been well studied. Investigation of cooperative control systems for deep-sea mining is still at an initial stage, sea trials for joint operation have not been conducted, and the stability and reliability of the control systems should be further studied.

Ore preprocessing equipment is designed to dehydrate the ore-seawater mixture transported from the seabed to ensure that the ore meets the water content requirements for transportation and the mineral loss is minimal. In addition, the ore preprocessing equipment should reinject the multi-stage processed seawater to the seabed through a pump to reduce the impact on the ecological environment. In China, research on ore preprocessing equipment for deep-sea mining is still in its infancy. The ore preprocessing equipment mainly dehydrates the ore by gravity. Studies on ore preprocessing equipment have been conducted by the China Minmetals Corporation and China Ship Scientific Research Center.

Ore storage–transport equipment is utilized to store the dehydrated ores temporarily in the cargo hold of the mining ship and transport the ores to the shuttle tank. Domestic research on ore storage–transport equipment for deep-sea mining is still in its infancy. There is no dedicated ore storage–transport equipment for deep-sea mining vessels. However, similar facilities used on land and self-unloading bulk carriers can be used as a design reference.

Launch and recovery equipment is mainly used to deploy mining vessels and buffer stations to the designated locations, and safely recover the facilities to the sea surface support vessels after mining operations. Carrying capacity and operational reliability are the key technical indicators for such equipment. In 2018 and 2019, China completed the sea trials of launch and recovery equipment. Shanghai Marine Equipment Research Institute and other research institutes have been engaged in the relevant research and even manufacturing of heavy-load launch and recovery equipment.

4 Issues of deep-sea mining equipment in China

4.1 Insufficient research on fundamental scientific issues and weak theoretical support

On one hand, the ability to analyze the dynamic characteristics of deep-sea mining systems in China is insufficient. There is an absence of effective analysis and prediction methods for the coupled dynamic response of the system under complex excitation conditions. On the other hand, owing to a lack of engineering experience and test data, structural characteristics of pipelines required for ultra-deep-sea operations have not been properly studied. R&D on high-performance materials and their construction or production capacity have also not been conducted for deep-sea ore transport pipelines.

4.2 Unverified key technologies and weak design capability of key equipment

At present, the real-time sensing technology for subsea environments is relatively weak. Owing to insufficient domestic technology, there is a certain dependence on foreign countries for key technologies and equipment. The R&D and manufacturing of long-distance ore lifting pumps is not comprehensive and the particle passing ability has not been verified for a long time, requiring further study. Heavy-load launch and recovery technology and heave compensation technology required in the operation process need to be developed until they are confirmed as stable and reliable.

4.3 Lack of R&D capabilities for underwater sensors and key components, and strong external dependence

There is a certain gap between China and other countries with regard to integrated navigation, positioning equipment, and algorithms. Deep-water positioning accuracy in China is insufficient. The domestic stability and reliability of high-power deep-sea cables and optical fiber technologies need to be improved. Deep-sea sensors, water-tight connectors, central control systems, and other key components are dependent on imports; the stability and reliability of domestic products need to be further improved.

4.4 Lack of joint sea trial for the entire system and unclear schemes for large-scale or commercial mining

Although China has conducted sea trials for individual deep-sea mining equipment, a joint sea trial for testing the entire system is extremely complex and challenging. No joint sea trial has been performed in China, which makes it difficult to fully verify the system design, key technologies, and underwater equipment. In addition, no large-scale sea trial has been conducted in China. Therefore, the production efficiency, stability, reliability, long-term operation, maintenance performance, and economy of the system have not been further studied.

4.5 Urgency to develop environmental assessment technology and environmentally friendly equipment

At present, developed countries have completed their environmental impact assessment of deep-sea mining and established an analysis and prediction method. China has not yet performed a complete environmental impact assessment for deep-sea mining, and has not proposed any assessment method. Furthermore, no comprehensive technical solutions have been developed for environmentally friendly mining and transporting equipment.

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5 Key scientific and technological issues and key R&D directions

5.1 Analysis of key scientific and technological issues

5.1.1 Overall design for deep-sea mining systems

The overall system design refers to the top-level design of a deep-sea mining system, including the system design and R&D, dynamic characteristic analysis during the mining operations, and dynamic response analysis in the launch and recovery processes.

System design and R&D denote the design of deep-sea mining equipment based on the mineral production capacity, including the design of sea surface support vessels, ore transport equipment, seabed heavy operation equipment, cooperative control system, and power systems, and minimalizing the impact on the marine ecology after realizing the basic functions.

The performance of the system needs to be dynamically checked to ensure operational safety after the completion of the overall system design. Specifically, the checks include the hydrodynamic characteristics of the overall system, structural dynamic characteristics of the connection between the sea surface support vessel and the pipeline, motion of the heave compensator, structural stress response and fatigue characteristics of the pump–pipe–buffer system, and mechanical characteristics of miner–seabed interaction.

The launch and recovery of mining vehicles are generally performed under mild sea conditions. On one hand, it is necessary to prepare a detailed launch and recovery plan according to the capacity of the sea surface support vessel, size of the moon pool, size and weight of the mining vehicle, etc. On the other hand, it is essential to perform a dynamic analysis of the mining vehicle motion and rope tension in the launch and recovery processes. Furthermore, it is necessary to fully consider the impact of the stress waves, which may induce a sudden increase in the cable stress during launch and recovery [13].

5.1.2 Perception and control of deep-sea heavy operation equipment

The deep-sea heavy operation equipment is the direct operating unit and at the “frontmost line” during deep-sea mining. In its most basic form, deep-sea heavy operation equipment comprises an environment perception system, control system, and execution system. The environmental perception system is the “eye” of the mining equipment, which makes preliminary judgments based on the surrounding environmental conditions and the distribution of seabed deposits; the control system is the “brain” of the operation equipment and controls the walking, turning, climbing, and collecting actions of the mining vehicle; the execution system mainly performs the mining operations, and includes traveling and collection devices.

The main task of the environmental perception system is to overcome the difficulties caused by high noise, high dust, and multi-particle scattering on the seabed. The system also has to conduct real-time environmental perception and measurement in the working area, thus laying the foundation for the enabling the walking and collecting actions of mining vehicles. From the perspective of perception, the environment perception system has to detect the seabed environment, mainly including the seabed topography and ore distribution. From the viewpoint of measurement, the system has to perform a rough measurement of the overall environment and accurate local measurement. From the perspective of implementation, environment perception can be achieved through optical and acoustic imaging technology.

Based on the sensing results, the control system commands the walking and collection of the operation equipment in real time, and maintains real-time communication and joint actions with the transport system and sea surface support vessel. In addition to realizing the basic functions of real-time control, the control system needs to perform intelligent calculations, including automatic path planning, automatic obstacle avoidance, and intelligent control algorithm execution.

5.1.3 Flow assurance of long-distance ore transport equipment

The key issues in ore transport equipment in terms of flow assurance include investigating the flow characteristics of the solid–liquid two-phase flow of large particles formed by ore particles and seawater while passing through hoses, hard pipes, and lifting pumps, forecasting and analyzing possible occurrences such as slug flow, blockage, and abrasion, and then proposing a reasonable optimization design or solution. Compared with offshore oil and gas exploitation, solid ore particles in long-distance transportation pipelines are of large size and high concentration, significantly increasing the impact force and abrasion of the particles on the pump impeller during the transportation process, and thereby the possibility of blockage in the pump-pipe equipment.

Another important problem of flow assurance is internal flow control and solutions in emergent status. It is necessary to analyze the status of the solid–liquid two-phase flow in the pump piping system and dynamic performances of key components, such as lift pumps and feeders, when the system stops and restarts. Finally, reasonable solutions should be proposed.

5.1.4 Maintenance and early warning for deep-sea mining system

During deep-sea mining operations, real-time monitoring of the working status of various equipment is required. Careful monitoring is required for: the positions, posture, and working status of the main equipment, such as the mining vehicle and ore transport equipment; the flow rate and concentration during the ore transporting process; real-time operation status and adjustments during ore preprocessing, exporting; and other processes to ensure the normal and orderly progress of deep-sea mining operations.

Another key technology is real-time monitoring and early warning of any mechanical failure in the system. During operation, monitoring the kinematics, stress, strain, and structural safety of the overall system of deep-sea mining is necessary to provide an early warning of the damage and fatigue status of the piping system by analyzing the dynamic characteristics of deep-water structures. Timely response and early warning with regard to various emergencies, such as sudden sea conditions, topographical changes, and biological interference, should be provided to avoid risks as quickly as possible and maximize the safety of the entire operating equipment.

5.1.5 Monitoring and assessment of environment impact

Environmental issues, including the impact on submarine ecosystems and plume spreading, cannot be ignored during deep-sea mining operations. Keeping the submarine ecosystems in focus, it is important to develop long-term biological ecological monitoring technology and equipment, study the evolutional characteristics of seabed biological communities, and build a seabed biological database. Considering seabed disturbances and plumes formed by tailings discharge, large-scale, high-resolution plume monitoring technology and equipment are required to study the diffusion and redeposition process of plumes to construct a plume real-time monitoring and tracking system.

Impact assessment on the seabed environment is another key issue that needs to be solved urgently in deep-sea mining. In view of the possible ecosystem impacts and plumes caused by mining operations, a technical system for environmental impact assessment has to be constructed through on-site observations, model tests, and numerical simulations to provide technical support for developing green and environmentally friendly deep-sea mining systems.

5.2 Key R&D direction of equipment

5.2.1 Heavy operation equipment for deep-sea mining

Considering the deep-sea deposits, deep-sea mining heavy operation equipment should be developed focusing on safe, stable, efficient, and green development concepts. Special attention should be paid to green mining, stable walking, intelligent control, and environmental perception to develop self-adaptive, highly efficient, and green collection technology for multiple deposits. In addition, stable walking technology should be developed for deep-sea heavy operation equipment for working under complex seabed conditions. In particular, it is essential to conduct research on the precision control technology of heavy operation equipment and real-time perception technology of the submarine environment with low illumination and high dust to realize intelligent and unmanned submarine operations.

5.2.2 Ore transport equipment

From the viewpoint of operational safety, transportation efficiency, and environmental protection of ultra-long-distance deep-sea ore transportation, large-flow, non-clogging, high-efficiency, and lightweight lifting equipment should be developed. It is important to develop flow assurance technology for multi-phase flow in long-distance pipelines and dynamic response forecast technology of ore transport equipment under multiple complex conditions. For commercial mining, it is essential to design an ore transporting system for long-term offshore operation and to develop maintenance, monitoring, and control technologies, as well as rapid offshore release and tie-back technologies responding to extremely harsh sea conditions.

5.2.3 Sea surface support equipment

From the point of view of safe and stable operations, and aiming for a goal of unmanned, informatized, and intelligent operations, it is urgent to master the technologies of collaborative control, navigation and positioning, monitoring and early warning, and launch and recovery throughout the entire lifecycle of the deep-sea mining system. In particular, we need to focus on the development of system-wide intelligent collaborative control technology, ultra-deep water high-precision integrated navigation positioning and data fusion processing technology, long-term real-

DOI 10.15302/J-SSCAE-2020.06.001

time monitoring and early warning technology, heavy operation equipment launch and recovery technology for complex sea conditions, multi-body coupling response forecasting technology, and accurate export technology.

6 Suggestions

6.1 Establish the concept of deep-sea mining development

Future developments in deep-sea mining equipment will adhere to the concepts of heavy load, collaboration, intelligence, and environmental safety, and accelerate the innovation of key technology and independent R&D of operation equipment in China. This means that it is necessary to develop high-power and high-efficiency subsea heavy operation equipment, achieve a breakthrough in the system-wide cooperative control technology for the subsea multi-equipment joint operation, build a subsea informatization, unmanned, and intelligent operation system based on information fusion, digital twins, and artificial intelligence technology, and green mining technology. The development of deep-sea mining is based on technological innovation, equipment research and development, offshore operations, ore processing, and comprehensive utilization to build a technological industry chain and realize commercial exploitation and industrialization.

6.2 Clarify the R&D tasks of key technology and equipment

Based on the development concept for China's future deep-sea mining technology and equipment, it is necessary to sort out the key scientific issues and the key and core technology, and clarify the urgent research tasks to be solved according to the research foundation and current R&D status in China. Aiming at the overall system for deep-sea mining, it is urgent to develop system-wide collaborative control technology, heavy-load launch and recovery systems, overall dynamic characteristics forecasting technology under complex sea conditions, environmental perception and precise control technology for seabed mining with heavy operation equipment, and large-flow, non-clogging, high-efficiency, and lightweight lifting pump equipment. It is also essential to focus on flow assurance technology for long-distance multi-phase pipe flows, forecasting technology for dynamic pipeline response under multiple complex excitations, and develop real-time monitoring and warning technology during the long-term production operations. In addition, regarding the environmental protection safeguards required in mining operations, it is essential to establish a technical system for environmental impact assessment.

6.3 Establish a demonstration project for deep-sea manganese nodules mining

Based on the main objectives of environmental protection and high-efficiency collaboration, it is important to design a demonstration project and conduct large-scale field tests in China's deep-sea exclusive MN exploration area. we suggest incorporation of detailed technical solutions for deep-sea mining and perform overall system design, integration, and fusion; development of mining equipment, ore transport equipment, sea surface control, and auxiliary mining equipment; establishment of a technical chain of exploration, mining, transportation, and transfer of seabed minerals by utilizing key technologies; establishment of a monitoring and evaluation system for the sea environment to achieve green mining. In addition, large-scale field tests should consider both CRC and SMS mining, providing offshore test platforms for related technology verification.

Commercial mining should be considered after a large-scale field test. Special attention should be paid to the economy, environmental protection, and system evaluation of deep-sea mining. Meanwhile, the operation and maintenance of a deep-sea mining system should be further considered for long-term operations at sea to ensure the establishment of a complete long-term operation, maintenance, monitoring, and controlling system. In addition, emergency measures and technology under extreme sea conditions should be considered, such as surface-underwater quick release and tie-back systems.

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