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Review

Research Status of Deep-Sea Polymetallic Nodule Collection Technology

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Abstract: The bottom of the ocean is rich in mineral resources, and deep-sea mining has been a research hotspot in recent years. As a key part of deep-sea mining operation, polymetallic nodule collection technology has been researched in many countries around the world. The distribution of deep-sea polymetallic nodule mining areas and the characteristics of nodules are summarized, which provides a reference for the study of collection technology and the optimization of pick-up device structure. In order to further establish a deep-sea mining collection technology system, the current development status of polymetallic nodule mechanical, mechanical–hydraulic composite and hydraulic collection technologies are summarized, and the analysis shows that hydraulic collection technology has a more promising commercialization prospect. For the hydraulic collection technology, the research progress of suck-up-based collection technology, Coandă-effect-based collection technology, double-row hydraulic collection sluicing technology and other collection technologies are summarized from three aspects: collecting principle, device structure parameter optimization, and sea trial situation, and the key technical problems of hydraulic ore collection are put forward. Through the comparative analysis of the pick-up efficiency, energy consumption, environmental disturbance and other performances of different devices, it is found that the Coandă-effect-based hydraulic collection technology has better comprehensive performance. A structural design evaluation indicator for the collection head of hydraulic collection technology is proposed, and the prospect of further research on hydraulic collection technology is put forward.

Keywords: polymetallic nodules; deep-sea mining; hydraulic collection technology; pick-up device structure optimization; pick-up efficiency

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1. Introduction

With the rapid development of society, the demand for mineral resources is increasing. The gradual depletion of land-based mineral resources has led mankind to focus its attention on the oceans and attempt to explore and develop seabed mineral resources [1]. The ocean floor is rich in mineral resources, including not only traditional oil and gas but also a variety of mineral resources that have not yet been fully recognized and utilized [2], mainly including polymetallic nodules, polymetallic sulfides and cobalt-rich crusts. Among them, polymetallic nodules, also known as manganese nodules, are mostly round or oval in shape, with a diameter of about 4~10 cm, mainly composed of manganese, but also contain other metal components such as nickel (1.3%), copper (1.1%), cobalt (0.2%), molybdenum (0.059%), and rare earth metals (0.081%) [3], which can be widely used in refining metallurgy, aerospace and other various industries. At the same time, due to its huge reserves and wide distribution, it has high mining potential and economic value [4].

Deep-sea mineral resource mining technology is a cutting-edge technology for the development of marine resources, marking the comprehensive ability and technical level in the development of marine resources of a country. A complete set of deep-sea mining systems can be further subdivided into collection technology, lifting technology, surface support technology and so on. Among them, as the key link in the technology chain of deep-sea mining systems, collection technology directly affects the yield of the mining system, the disturbance of the system to the seabed environment and other factors, which is of great significance to research and has become a research hotspot in recent years. At present, countries and organizations around the world have carried out a lot of research on different collection technologies, but there is still a long way to go before commercial mining. Existing research reviews mostly focus on the deep-sea mining system as a whole, but are not specific enough about the collection technologies, and lack a more detailed organization and generalization.

This paper focuses on the collection technology in deep-sea mining systems, firstly summarizing the resource distribution and nodule characteristics of deep-sea polymetallic nodules, then summarizing the current development status of mechanical, mechanical–hydraulic composite, and hydraulic collection technologies, and then introducing several different collection schemes in hydraulic collection technology from the principle of collection, parameter optimization, and sea trial situation one by one. Finally, this paper summarizes the key problems of hydraulic collection technology, then compares and analyzes the overall performance of different hydraulic collection devices, puts forward the research difficulties of hydraulic collection technology and a kind of evaluation indicator system for parameter optimization of the hydraulic collection device, and provides reference suggestions for the further development of collection technology.

2. Distribution and Characterization of Deep-Sea Polymetallic Nodule Resources

2.1. Distribution of Polymetallic Nodule Resources

Polymetallic nodules are mainly found on the surface of abyssal plains covered by sediments at water depths of about 3500 to 6500 m, with the nodules half-buried or completely buried in the sediments. About 15 percent of the ocean floor is covered by polymetallic nodules, including about 23×10^6 square kilometers in the Pacific Ocean, 15×10^6 square kilometers in the Indian Ocean and 8×10^6 square kilometers in the Atlantic Ocean, with a total nodule reserve of about 3 trillion tons [5]. According to the geomorphological features of the ocean floor, the tectonic position and the abundance, composition and geochemical characteristics of polymetallic nodules, the oceans of the world are divided into 15 polymetallic nodule-rich zones, of which 8 are in the Pacific Ocean, 3 in the Atlantic Ocean and 4 in the Indian Ocean [5].

Among them, the Pacific Ocean has three of the best-known polymetallic nodule-rich zones: the Clarion–Clipperton Zone (CCZ), Peru Basin, and the Penryn Basin (including the Cook Islands exclusive economic zone). A large nodule-rich zone has also been identified in the Central Indian Ocean Basin (CIOB) [6]. Due to the high rate of sedimentation in the Atlantic Ocean, nodules are not able to develop extensively in most areas, resulting in relatively few polymetallic nodules in the Atlantic Ocean. There may also be nodule fields in the Argentine Basin in the south-west Atlantic and in the Arctic Ocean, but these areas have been less explored [3,6,7], The distribution of the main mining areas of polymetallic nodules globally is shown in Figure 1.

Currently, in addition to resource exploration within their respective territorial waters, countries can also obtain polymetallic nodule exploration contract areas with exclusive exploration rights and preferential mining rights in the high seas areas enriched by mining areas such as CCZ. In 2001, China Ocean Mineral Resources R&D Association (COMRA) signed a contract with the International Seabed Authority (ISA) to acquire a 75,000 square kilometers area of China, located in the western part of the nodule belt in the CCZ [8,9]. In recent decades, Chinese scholars have conducted a number of studies on the pioneer area of China [10,11], focusing mainly on the coverage of polymetallic nodules in mining areas.

The coverage rate of polymetallic nodules refers to the percentage of polymetallic nodules covered in a certain area of the seabed surface, which is an important indicator to evaluate the resource richness of mining areas. Before the 21st century, China mainly carried out exploration through the methods of cableless grab sampling and multi-frequency acoustic detection. The grid spacing used in this method was too large, the precision was low and the distribution of nodules was characterized only qualitatively. In 2002, Bao et al. [12] used the deep drag system for acoustic data collection and processing and found that the coverage rate of polymetallic nodules in the western area of China's pioneer area was significantly higher than that in the eastern area. Only 7.9% of the coverage rate of the eastern area is greater than 25%, and 39.3% of the coverage rate of the western area is greater than 40%. Areas with coverage equal to 0% are classified as one phase, while others are classified according to 5% coverage. There was a large mutation in the coverage rate of the eastern area, with an average phase change of 451 m, while the western area was dominated by a gradual change, with an average phase change of 908 m. The phase change refers to the distance between two phases with adjacent coverage rates. In 2014, Liang et al. [9] conducted a study on the small-scale distribution characteristics of nodules in the western area and found that the coverage rate of polymetallic nodules in the most western area was between 40 and 60%, with little change in the east–west direction, and an increasing trend from north to south.

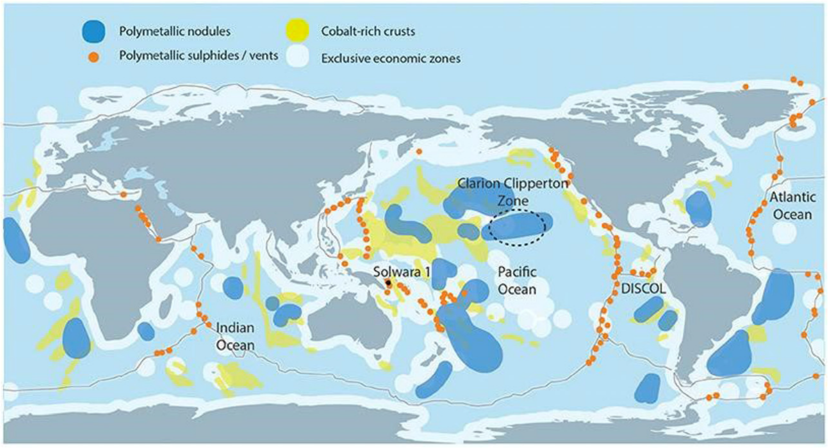


Figure 1. Distribution of the main mining areas of polymetallic nodules (reproduced from [7], with permission from MDPI, 2022).

In the process of conducting research on collection technology, national researchers should also focus on the pioneer areas where their countries and research institutions have exclusive exploration rights and priority mining rights, as well as on polymetallic nodule-rich areas within the territorial sea, and it is recommended that surveys be carried out on the seafloor conditions, the ecological environment and the rate of nodule coverage in pre-mining areas so that targeted efforts can be made to optimize the design of the collection system and the structure of the collection head.

2.2. Polymetallic Nodule Characteristics

The yield of deep-sea polymetallic nodules is one of the most important indicators of the advancement of collection technology and is directly related to the collection efficiency of the collection system. The physical characteristics of the nodules, such as shape, size and mass, as well as the hydrodynamic characteristics of the nodules, are key factors which affect the collection efficiency and need to be considered in the design process of the collection device.

Polymetallic nodules are mostly black or dark brown in color and vary in shape, as shown in Figure 2, most of which are irregular spherical and ellipsoidal, as well as cauliflower-like, flat, platy, conjoined, etc. [8,13]. According to the diameter of the long axis, most of the nodule particles are between 1 and 10 cm, and a few can reach more than 10 cm in diameter, with a density of about 2000 kg/m^3. The distribution of polymetallic nodules in the seabed of each mining area is different, but the distribution law is roughly similar. In 1993, Morgan [14] et al. analyzed 5358 nodules sampled by the Ocean Minerals Company (OMCO) from 1978 to 1981 on 16 voyages in CCZ, and obtained the lognormal distribution diagram of nodules size and the distribution law of nodules particle size:

$$\ln N = Y_0 - (B/2G)D \quad (1)$$

where N is the number of nodules, D is the size of nodules, Y_0 is the intercept, B is the nodule burial rate, and G is the nodule growth rate.

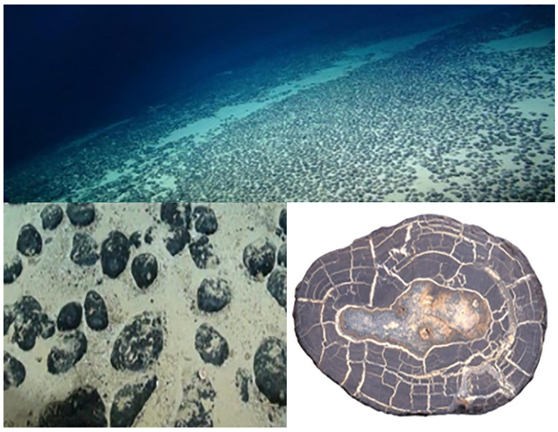


Figure 2. Polymetallic nodules on the seabed (reproduced from [1], with permission from Elsevier, 2020).

In 2017, T. Yamazaki [15] used data from the Central Pacific Basin to obtain the Weibull probability distribution of the long axis diameter of nodules and the Gaussian probability distribution of the cumulative weight of nodules with the long axis diameter, among which the average size of 1570 nodules reached 3.2 cm, as shown in Figure 3. In 2019, Kim et al. [16] used the data of polymetallic nodules from 47 stations in the KR5 block of CCZ to calculate the histogram of the nodule size and mass. After comprehensive consideration of a variety of candidate edge distributions and correlation functions, the probability density function of the average size and mass of manganese nodules in this area was obtained by the Copula method. It was concluded that the particle size of most nodules was less than 7 cm, and the particle size and mass distribution showed a left-leaning trend.

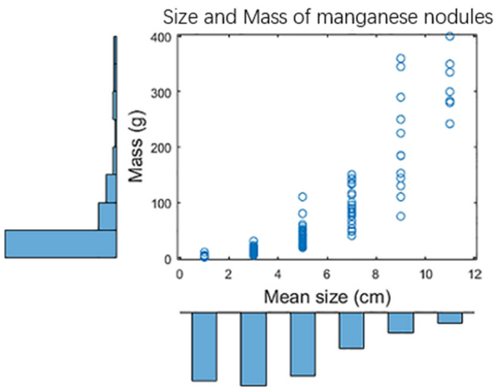


Figure 3. Weibull distribution of nodule size and histogram of nodule size and mass (reproduced from [16], with permission from Elsevier, 2019).

In 2000, Tao et al. [17] conducted a preliminary analysis of the particle size of polymetallic nodules in the mining area of China in CCZ and found that their particle size distribution had fractal characteristics, and further studied the linear equations of the spatial distribution, particle size and weight distribution of nodules. In 2017, Zou et al. [18] carried out further research on the characteristics of nodules in the pioneer area of China and found through experimental tests that the average porosity of polymetallic nodules was 43.71%, the compressive strength was 346–2286 kPa, and the surface of nodules were 9.8% smooth type, 58.8% smooth–rough type, and 31.4% rough type. At the same time, the team also studied the hydrodynamic characteristics of polymetallic nodules, and proposed to test the effective gravity of nodules by experiment, calculate the resistance coefficient of nodules, and calculate the settlement velocity of nodules in still water:

$$W_t = 1.503 S_f^{0.815} \left(gd \frac{\rho_s - \rho_w}{\rho_w} \right)^{0.5} \tag{2}$$

where W_t is the particle settling velocity, S_f is the particle shape coefficient, ρ_s and ρ_w are the density of particles and water, respectively, and d is the particle diameter.

A polymetallic nodule is a collection object of collection technology. Its physical characteristics such as shape, size, mass, density and hydrodynamic characteristics such as resistance coefficient and settling velocity are of great reference value in the structural design of the collection device. The size and mass distribution of nodules detected through the solid sea of each voyage can be used in the simulation and experiment of collection technology and provide a reference for the selection of nodules, so as to simulate the submarine environment more truly. At the same time, the nodule itself plays an important role in the selection of collection technology, especially in the design and optimization process of the collection head.

3. Introduction of Polymetallic Nodule Collection Technology

In recent decades, researchers from various countries have carried out a lot of research and sea trials and put forward four kinds of collection systems that can be used to mine deep-sea polymetallic nodules, namely submarine-drag buckets, continuous line buckets, shuttle vessels and pipeline lifts [19]. The schematics of the four acquisition systems are shown in Figure 4. The submarine-drag collection system is mainly moved on the seabed by the mining ship dragging the bucket and then lifted to the ship by the towing cable. The continuous line bucket collection system is an improvement on the towing bucket, which can be continuously raised to the mining vessel by a cable. The shuttle vessel collection system is mainly operated in a cyclical floating shuttle operation, collecting enough ore on the seabed and then floating to the surface of the water to unload the ore to the mining ship. After many sea tests [20–22], the above three operating modes generally have problems such as low acquisition efficiency, low economy and poor reliability, so they are gradually eliminated with the advancement of research. The pipeline lift collection system mainly obtains nodules from the seabed with a collecting device and lifts the nodules from the seabed to the mining ship using hydraulic or pneumatic means. Compared with the previous three, this system has the advantages of simple structure, good operation continuity and high economy, and is the mainstream polymetallic nodule collection system in recent years [23–27].

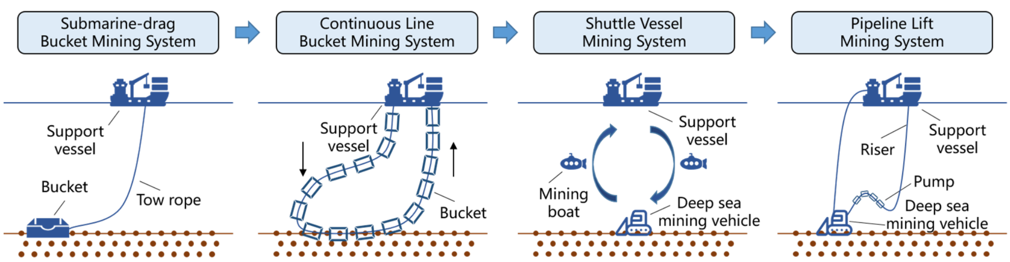


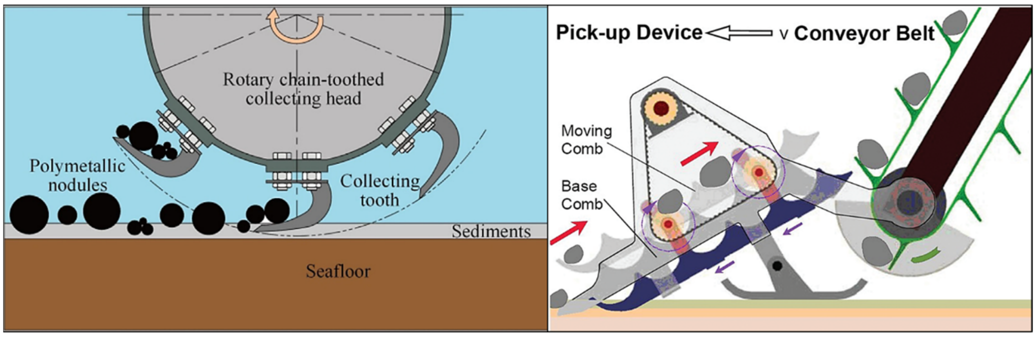
Figure 4. Four kinds of polymetallic nodule collection systems.

In order to further improve the economic benefits, collection efficiency and structural reliability of the pipeline lift collection system, researchers have developed a variety of nodule collection technologies for the structure of the collection head [28–32]. The different ways of collecting polymetallic nodules are mainly divided into mechanical, mechanical–hydraulic composite and hydraulic collection technologies.

3.1. Mechanical Collection Technology

Mechanical collection technology mainly uses mechanical structures to mine polymetallic nodules. By means of a brush, shovel, rake, etc., the polymetallic nodules on the seabed surface are scooped up and transported to the pipeline through toothed combs and other structures to achieve the collection of polymetallic nodules.

In 1976, the Ocean Minerals Company (OMCO) developed a mechanical mineral particle collection device and conducted sea trials, and its schematic diagram is shown in Figure 5a [2,33]. The scheme digs nodules from the seabed surface through a rotating chain tooth mechanism and delivers them to the mining car, and the cutting depth of the seabed surface can be controlled by raising or lowering the device. The prototype completed the process of ore picking, washing, crushing and pumping during the sea test [33]. In 1987, the IMB Institute of the University of Karlsruhe in Germany designed a mechanical acquisition structure [29] and experimentally tested the wear of the toothed mechanism at higher speeds and the acquisition performance of the device. In 2001, the Institut für Konstruktion Siegen (IKS) of Germany summarized the advantages and disadvantages of the mechanical ore collecting devices developed in previous countries and designed a better collecting head form, as shown in Figure 5b [29,34]. The collection head consists of a shovel-like frame whose toothed structure cuts forward into the seabed and brings up nodules. As it continues to move forward, the particles are gradually transported to the mechanically driven comb structure at the rear end, which is eventually lifted and moved into the car. The collection head is equipped with a vibrator on the frame, which enables the shovel frame and comb structure to remove sediment through mutual movement.



(a) (b)

Figure 5. Mechanical collection device. (**a**) OMCO (1976) (reproduced from [2], with permission from Elsevier, 2023); (**b**) IKS (2001) (reproduced from [34], with permission from Elsevier, 2023).

Mechanical collection technology mainly achieves the purpose of picking nodules through the direct mechanical action of a collection device on the seabed. The collection efficiency of this technology is usually high, but it has serious damage to the seabed environment, and it also has some problems such as easy wear of moving components, easy blockage of the collection inlet, and poor environmental adaptability. In recent years, fewer and fewer studies have been conducted on this technology. Because the device does not directly contact with the seabed, the hydraulic collection technology is less destructive to the environment and has higher economic benefits, so it is considered to have more commercial prospects. In the process of transition from mechanical collection technology to hydraulic collection technology, some countries put forward the mechanical–hydraulic composite collection technology and carried out related research [29,35,36].

3.2. Mechanical–Hydraulic Composite Collection Technology

Mechanical–hydraulic composite collection technology, first through hydraulic collection technology, such as Coandă-effect-based collection technology and double-row hydraulic sluicing collection technology, to lift the polymetallic nodules from the seabed surface, and then through the mechanical structure to the mining car, can effectively avoid direct contact between the collection device and the seafloor.

In 1992, the VersuchsanstaIt für Wasserbau und Schil1bau (VWS) in Berlin, Germany, developed a mechanical–hydraulic composite collection device [29], the bottom end of the collection head uses a wall-attached jet hydraulic structure to wash and lift nodules, and then transmits them to the mining car through a mechanical belt. This prototype has only been simulated, and has some shortcomings such as high power consumption, and has not been carried out relevant sea trials. Korea Institute of Ocean Science and Technology (KIOST) has carried out a lot of research on the hydraulic–mechanical composite collection device by combining the advantages of high mechanical collection efficiency and simple hydraulic structure with high reliability [35,36]. This team used two kinds of hydraulic collection technology, double-row hydraulic sluicing and Coandă-effect-based, respectively, to peel and lift the nodules, and then transport the particles to the mining car through the tooth chain structure. From 2009 to 2010, a comprehensive sea trial was carried out on the MineRo-I mining vehicle, which adopts the mechanical double-row hydraulic sluicing composite collection technology. From 2011 to 2013, the MineRo-II mining vehicle, which adopted the mechanical Coandă-effect-based composite collection technology, successfully carried out nodule mining at a seabed depth of 130 m, further tests at a seabed of 1370 m, and a detailed study on the walking capacity of the mining vehicle.

Although the mechanical–hydraulic composite collection technology integrates the mechanical collection technology and the hydraulic collection technology, the damage rate of the collection head and the energy consumption required for improving nodules are reduced, but there are also some problems, such as the height of the collection inlet from the seabed surface, which should not change too much, otherwise the collection efficiency will be affected, and the fact that nodules with large diameters cannot be mined. At the same time, it is difficult to determine the parameters of the hydraulic collection system and the shape of the flow channel, and a large number of simulations and tests are needed to modify and optimize the system before it can be put into use. The device structure is still relatively complex, the reliability and continuous working ability of the device in the deep-sea environment are still huge challenges, and there is still a long way to go before it is put into commercial exploitation [37]. At present, only a few countries are still carrying out relevant technical research.

3.3. Hydraulic Collection Technology

Due to the simple structure and high reliability of the device, the hydraulic collection technology can meet the needs of long-term continuous work and has great commercialization potential. In recent years, scholars from various countries have carried out a lot of research [30,38–42]. Hydraulic collection technology relies on water jets to achieve the stripping and lifting of polymetallic nodules. Its principle is to use a water jet to generate negative pressure or to separate polymetallic nodules from bottom sediments and then lift nodules through suction flow. According to different starting modes of nodules, the hydraulic collection technology can be subdivided into suck-up-based collection technology, Coandă-effect-based collection technology, double-row hydraulic sluicing collection technology and other collection technologies. The following will be introduced from the collection principle of these collection technologies, the optimization of device structure parameters and related sea tests [41,42], respectively.

3.3.1. Suck-Up-Based Collection Technology

The principle of suck-up-based collection technology is to collect lifting nodules by means of hydraulic suction, as shown in Figure 6. This technology uses a suction pump to extract the nodules through a suction port and transport them to the upper pipe.

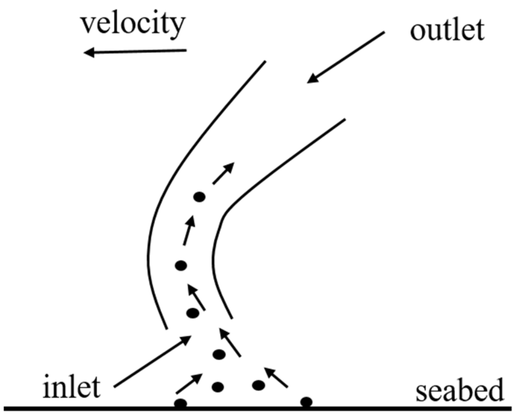


Figure 6. Principle figure of suck-up-based collection technology.

At present, some scholars have optimized the structural parameters of the suck-up-based collection head to further improve the collection efficiency of the device. Hu et al. [38] investigated the flow field information around devices with and without balls during particle initiation using a particle image velocimetry (PIV) system. They proposed that the vertical flow velocity of the device increases exponentially with the distance from the bottom in a certain area. Yue et al. [30] studied the influence of flow rate and drag speed on collection efficiency, and verified the feasibility of the numerical method by comparing simulation and experiment. In addition, the turbulent kinetic energy and diffusion distribution of gb sediment–seawater mixture are simulated, and it is concluded that the suck-up-based collection head has less disturbance to the flow field. Cheng et al. [39] studied the influence of different-shaped inlets on collection efficiency and concluded that the straight bobbin with a flange inlet shape has a higher collection efficiency than the straight bobbin without a flange inlet shape. Using the SST-DES model to simulate, we found that the flange inlet shape makes the negative pressure area at the top of the ball larger and has greater lift force. Zhao et al. [40] proposed a new collection device based on the principle of spiral flow and studied its performance, as shown in Figure 7. The numerical simulation method is used to optimize the design of the arc plate structure, and the accuracy of the optimization design is verified by experiments. It is found that the device has advantages in increasing suction and critical bottom clearance, thereby minimizing the operating flow. Based on the characteristics of suction and particle movement, a prediction model of collection performance was established to achieve an accurate collection of nodules. The optimization design of the structure of the collection head mainly considers the parameters of suction flow rate, inlet shape, drag speed and the related research of particle lifting mechanism.

In view of the suck-up-based collection technology, many countries and associations have applied it to the mining vehicle for sea tests. In 1977–1978, Ocean Mining Associates (OMA) used the suck-up-based collection principle to conduct sea trials at a depth of 4880 m and proved the feasibility of a complete collection system of "submarine nodulation stripping—pipeline transport lifting—surface ship storage" [41]. In 2000, the National Institute of Ocean Technology (NIOT) of India and Siegen University of Germany jointly developed a collection prototype for sea trials. In the collection process, the mechanical arm drives the sawtooth collection head to rotate and cut, loosen the seabed sand, and realize particle lifting through pump in Figure 8a [42,43]. During the experiment, the layout and recovery of the prototype encountered difficulties, and in 2006, the team conducted a second sea test at a depth of 451 m after the overall improvement of the collection device.

In the secondary sea test, the overall mobility of the collection system was enhanced, and the maximum mining capacity reached 12 t/h, as shown in Figure 8b [42,43].

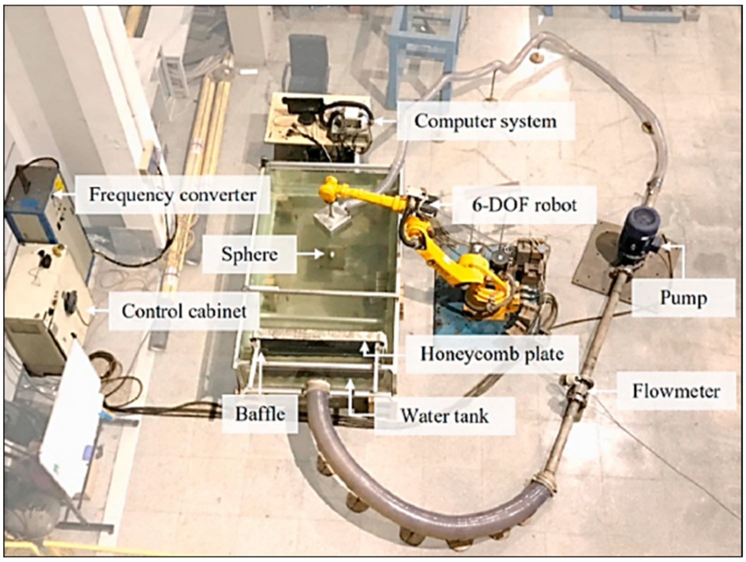
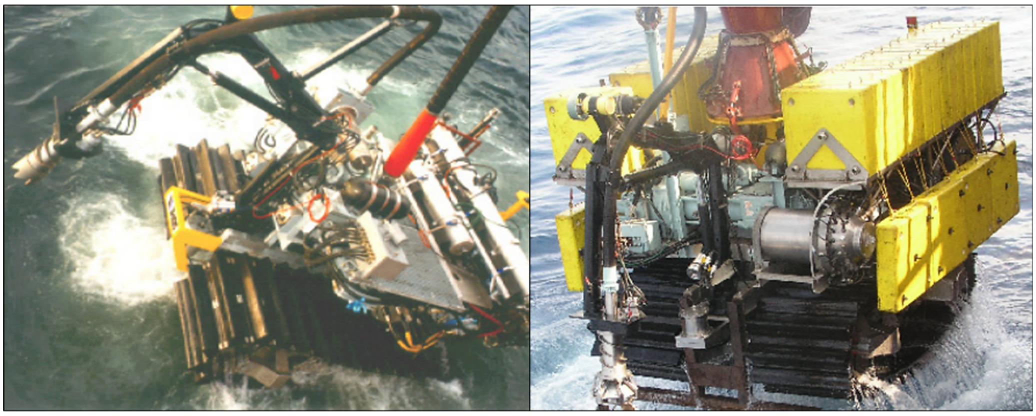


Figure 7. Experimental research on optimization of suck-up-based collection device structure (reproduced from [40], with permission from Elsevier, 2021).



(**a**) (**b**)

Figure 8. Suck-up-based mining machine (reproduced from [43], with permission from Elsevier, 2021) (**a**) NIOT prototype (2000); (**b**) NIOT prototype (after improvement) (2006).

3.3.2. Coandă-Effect-Based Collection Technology

The basic principle of Coandă-effect-based collection technology is to use the Coandă effect to lift the nodules. The Coandă effect, also known as the wall-attachment effect, was named by the Romanian inventor Henri Coandă; it is when a fluid changes from flowing in its original direction to flowing on a raised surface. Due to the change in flow direction, a low-pressure area is created around the fluid. The principle is applied to the collection technology, and the collection flow field is mainly obtained by the coupling of the jet flow field and the suction flow field. The characteristics of this type of device are that the jet dip angle is small, the jet flows against the wall, and the pressure difference generated on both sides of the arc plate is used to lift the nodule particles, as shown in Figure 9.

The collection capability of the Coandă-effect-based collection head is usually related to the structural parameters, particle diameter and traveling speed of the collection head, and the optimization of these parameters can significantly improve the collection efficiency of the device. In 2022, Jia et al. [44] proposed a simplified Coandă-effect-based model, which is shown in Figure 10a, and obtained its solution in approximately closed form. They proposed that the collection efficiency of the device is related to the lift of nodules, verified the theoretical model by using the CFD-DEM method, and concluded that at higher initial velocity, higher dimensionless jet groove height and lower dimensionless wall height, the Coandă effect will increase. In 2023, this team studied the shape of the arc plate of the collection head [45], as shown in Figure 10b, generalized the traditional cylindrical wall to the logarithmic spiral wall, studied the influence of wall curvature on particle lift, and found that the Coandă effect would be stronger at higher jet velocity, larger local curvature and higher jet groove height. Yang et al. [46] explored this and concluded that the increase in jet angle can enhance the uniformity of the flow field at the bottom of the collection head, and the increase in the convex curved wall radius can improve the overall uniformity of the flow field inside the collection head. Finally, the optimal collection efficiency can be achieved when the height off the bottom is 80 mm, the jet angle is 45°, the convex curved wall radius is 350 mm, and the moving speed is 0.5 m/s. Zhang et al. [47] carried out a study on the optimization of the geometric parameters of the collection head in order to improve the collection efficiency of the device, verified the feasibility of applying the CFD-DEM numerical simulation method based on experiments, and studied the influence rules of three dimensionless parameters (the ratio of the convex wall curvature radius of the device to the particle diameter, the ratio of jet thickness to the particle diameter, and the tangential radian of the jet) on the jet flow rate.

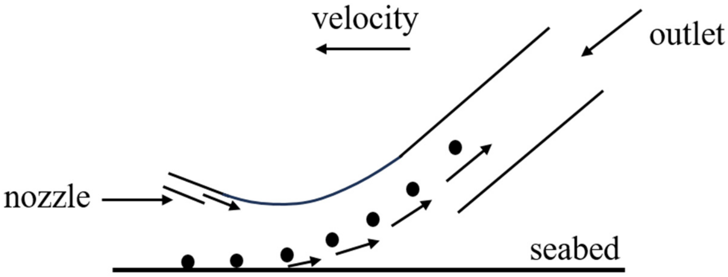
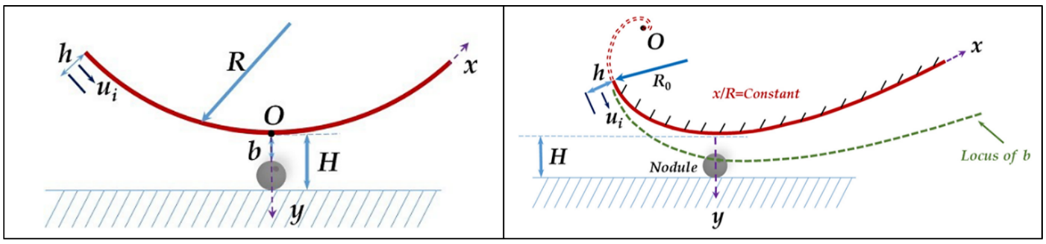


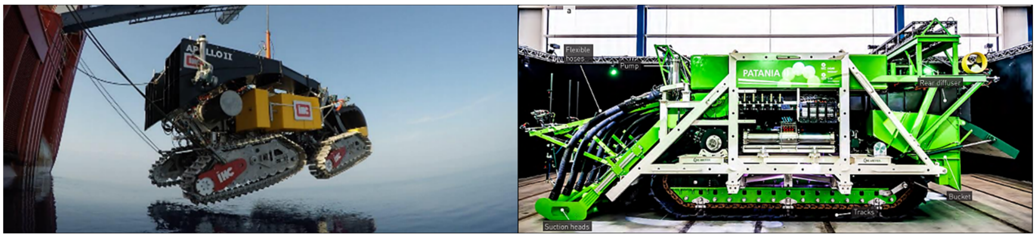
Figure 9. Principle figure of Coandă-effect-based collection technology.



(**a**) (**b**)

Figure 10. Research of the shape of the arc plate of the collection device. (**a**) Cylindrical wall (reproduced from [44], with permission from MDPI, 2022); (**b**) logarithmic spiral wall (reproduced from [45], with permission from MDPI, 2023).

For sea trial prototypes, in 1976, Ocean Management Incorporated (OMI) [31] evaluated the performance of different types of collection systems through sea trials, achieved a collection efficiency of 40 tons/h, and collected about 800 tons of nodules from a depth of 5250 m. It was proposed that hydraulic collection technology has higher collection efficiency, can better adapt to changes in seabed conditions, and has a high commercial prospect. In 2018, the Blue Nodules project [48], funded by Royal IHC and others in the Netherlands, also aims to reduce environmental impact by conducting sea trials of the Apollo II mining vehicle at a depth of 300 m in the Mediterranean Sea, using a wall attached jet collection head and an altitude control system to control the position of the collection head relative to the sea bed, as shown in Figure 11a. In 2019, Global Sea Mineral Resources (GSR) conducted tests in the CCZ in April, integrating the walking system and collection system of the vehicle for the first time, collecting 1550 tons of polymetallic nodules over 107 h of operation on the seabed, as shown in Figure 11b. This sea trial assessed for the first time the potential environmental impact of seabed nodule mining operations, greatly advancing the current understanding of suspended sediment plumes [49], and also reflecting that Coandă-effect-based collection technology is a hot research topic in recent years.



(**a**) (**b**)

Figure 11. Mining machine of Coandă-effect-based collection technology. (**a**) Apollo II (2018) [48]; (**b**) GSR (2019) [49].

3.3.3. Double-Row Hydraulic Sluicing Collection Technology

Double-row hydraulic sluicing collection technology mainly uses two rows of nozzles at the front and back of the collection head to eject jets. The jets hit the seabed surface in an oblique direction, converge in the middle area and rise, driving the surrounding fluid to converge in the middle and then flow upward into the pipe. The water carries the ore particles upward and finally achieves the stripping and lifting of the ore particles. Its working principle is shown in Figure 12.

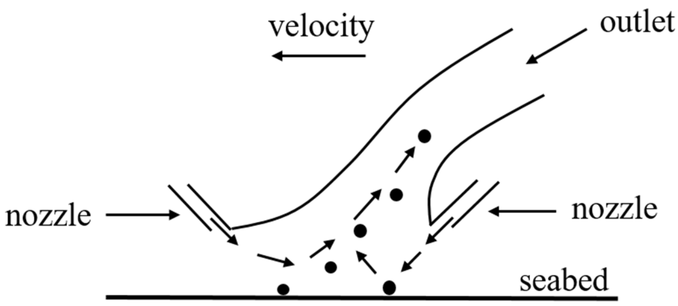


Figure 12. Principle figure of double-row hydraulic sluicing collection technology.

At present, many scholars have carried out research on the structure of double-row hydraulic sluicing collection devices. Hong et al. [32,50] studied the influence of the baffle shape, bottom height, forward speed and nozzle flow of the collection head on the collection efficiency through experiments, obtained the pressure distribution at the bottom of the collection head, and concluded that the position and shape of the baffle were the main influencing factors of the collection efficiency. Yang et al. [51] gave the main structural parameters and determination methods of the inlet of the collection head, the baffle plate and the conveying pipeline. Through experiments, the influences of the advancing speed, nodule abundance and the height of the front nozzle from the bottom on the collection efficiency and sediment content were studied, and it was concluded that the jets from the front and rear nozzles played an important role in the trapping of the nodule. Guan et al. [37] introduced the determination methods of jet reverse angle, the distance between front and rear nozzles and other parameters, and verified them by using the parameters of previous collection heads. Through comparison, a better parameter range of the device was obtained, but further parameter optimization was required for specific mining area characteristics. Zhang et al. [52] studied the changes in jet angle, suction velocity, post-jet velocity and other parameters on the internal flow field of the collection head, and obtained a set of structural parameters of the collection head with better structure and a better internal flow field effect. Liu et al. [53] analyzed the effects of jet velocity and nozzle particle size on the local flow field, bed shear force and collection energy efficiency, and divided the flow field around the collection head into the submerged jet zone, impact zone and wall jet zone. Considering the collection efficiency and energy efficiency of the device, it is recommended that the jet velocity of the collector be 8–9 m/s. Nozzle spacing, jet angle, jet velocity and baffle shape are the main influencing factors for the design and optimization of double-row hydraulic sluicing collection devices.

Aiming at double-row hydraulic sluicing collection technology, some countries have applied it to mining vehicles for sea tests. In 2018, the Changsha Research Institute of Mining and Metallurgy developed a new generation of deep-sea polymetallic nodules collector “Kunlong 500”, carried out a 500 m sea level test, and drove a maximum distance of 2881 m in a maximum water depth of 514 m, as shown in Figure 13. The underwater operation time was 7 h 56 min and the bottom operation time was 5 h 34 min. With a positioning accuracy of 0.72 m, the track mechanism completed the drawing of the “China Star” with a unilateral length of 120 m on the seabed according to the planned path [54].

Figure 13. Kunlong 500 mining vehicle and trajectory (reproduced from [54], with permission from MDPI, 2021).

3.4. Other Collection Technology

In addition to the suck-up-based, Coandă-effect-based and double-row hydraulic sluicing collection technologies that have been studied more, the development of new collection technology is also a recent research hotspot. Liu et al. [55] designed a suction-disc-type hydraulic collection device with four tangential jet nozzles based on the hydrodynamic characteristics of the vertical axis vortex and proposed a new collection method by using a tangential jet to induce the vertical axis vortex in the collection device. This team studied the collection rate and particle movement trajectory of the device under three different swirling degrees and tested the collection performance of the prototype through a 10 m deep pool, and found that the collection capacity of a single collection head reached 34.13 kg/min.

In addition, the robotic collection system has been successfully used in sea trials in recent years. IMPOSSIBLE METALS has developed an autonomous underwater vehicle (AUV), the Eureka 1 [56]. This device floats near the seabed, identifies polymetallic nodules by means of a camera and an artificial intelligence system, and starts selective harvesting of marine minerals by means of robotic arms. The device minimizes disturbance to the seafloor environment and avoids the generation of large plumes, as it does not use water currents to directly scour the seafloor surface. At the same time, the device is highly scalable and can be arrayed to increase the yield of the harvesting, which has some prospects for commercialization.

Through the above analysis, mechanical and mechanical–hydraulic composite collection technology has many problems that are difficult to solve, and there are few related technical studies that are not suitable for commercial mining in the current environment. Since the development of hydraulic collection technology, it has been further refined into suck-up-based collection technology, Coandă-effect-based collection technology and double-row hydraulic sluicing collection technology, etc. Scholars from all over the world have carried out relevant research through simulation, experimental testing and sea trials, and confirmed that this technology has great commercial potential. In the development process of hydraulic collection technology, many key technical problems have been concentrated and focused on solving, mainly including particle lifting mechanisms, impact jets, multi-parameter comprehensive optimization and sediment disturbance, etc. The following will introduce and analyze each technology.

4. The Key Problem of Hydraulic Collection Technology

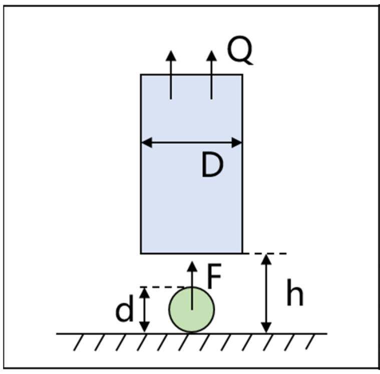
4.1. Research of Particle Lifting Mechanism

Deep-sea polymetallic nodules are half-buried or fully buried in the surface of the sea floor, and the stripping and lifting of the particles is the first step of ore collection technology, and it is also the key to hydraulic collection technology. Many scholars have studied the force, starting mechanism and flow field characteristics of the particles under the action of hydraulic suction. See Table 1.

Table 1. The key problem of hydraulic collection technology.

The Key Problem	Research Method	Specific Research Content
Research of particle lifting mechanism	Simulation and experiment	The particle force, starting mechanism and flow field characteristics are analyzed to optimize the structure of the collection device and improve the collection ability of the device.
Research of impact jet mechanism	Simulation and experiment	The collection efficiency and bottom disturbance of the device are studied by changing the parameters of the jet nozzle angle, shape and flow rate.
Research of multi-parameter comprehensive optimization	Simulation	Global optimization method is adopted to reduce device power consumption and improve collection efficiency.
Research of low disturbance of sediment	Simulation and experiment	Different sediment simulation methods were set up and compared with experimental tests to carry out relevant research on sediment disturbance simulation.

Xiong et al. [57] studied the settling and floating motion of spherical particles in vertical pipes by using the CFD-DEM method, verified that the method was suitable for the study of large-particle solid–liquid two-phase flow, and revealed the relationship between particle size and settling and suspension velocity, as well as the relationship between drag coefficient and Reynolds number, as shown in Figure 14a. Zhao et al. [58–60] studied the suction force and surrounding flow field characteristics of spherical particles under suction. The critical bottom clearance of particle starting is measured experimentally, and the influence of the parameters such as the bottom clearance, particle diameter and the angle between the inlet of the collecting pipe and the particle on the force of the particles is studied. An empirical model of collection performance prediction is established. The empirical formula of vertical force and the criterion formula of vertical motion of the particles are obtained under the condition of a maximum tolerance of less than 15%. At the same time, the forces acting on spherical particles are predicted by numerical simulation and verified based on experimental results, as shown in Figure 14b. Chen et al. [61] used the PIV method to study the effects of particle size, bottom height of collection pipe and other parameters on the starting velocity and flow field distribution of single spherical particles. The study showed that spherical particles would reduce the flow field velocity of the lower part of the particles, resulting in a larger velocity gradient and pressure gradient. Xia et al. [62] carried out a numerical simulation study on the starting characteristics of spherical particles under vertical pipeline suction, analyzed the change law of wake flow and vortex structure with particle movement, and obtained the critical velocity and critical lifting force of particle starting under typical ore collection conditions. The results show that the movement of particles with the peak resistance coefficient and Reynolds number at the pipe entrance tends to be stable after entering the pipe. The wake and vortex of particles gradually evolved with the movement of particles, and because the separation point of the wake vortex of particles was near the top of the sphere, the vertical force exhibited oscillatory characteristics near the mean value. Chen et al. [63] experimentally studied the motion characteristics of a thick ball with a radius of 2 cm under the suction action of a vertical pipe and found that the ball rose in a spiral trajectory, and the tangential motion of the ball was conducive to hydraulic collection. The flow field information is calculated using the CFD-DEM method, and it is concluded that the vortex around the sphere and its coupling with the main stream are the main reasons for the extra lift exerted on the sphere. Zhang et al. [64] studied the problem of critical suction velocity in the process of hydraulic lifting of seafloor coarse particles through experiments and proposed the calculation formula of critical suction velocity. Ren et al. [65] based on the method of CFD-DEM, studied the motion and mechanical properties of coarse particles under different flow velocities, particle sizes, and distance between particles and inlets, and proposed that the spiral phenomenon of particles is caused by centripetal force, and the rise of particles is the result of competition between fluid resistance and relative gravity. At present, the main way is to combine simulation and experiment, and combine with PIV technology and so on to carry out the research related to the mechanism of particle lifting. At present, the particle lifting mechanism is mainly studied through the combination of simulation and experiments, PIV technology, etc. This technology provides important theoretical support for the collection capacity and collection efficiency of the device in the hydraulic collection technology.



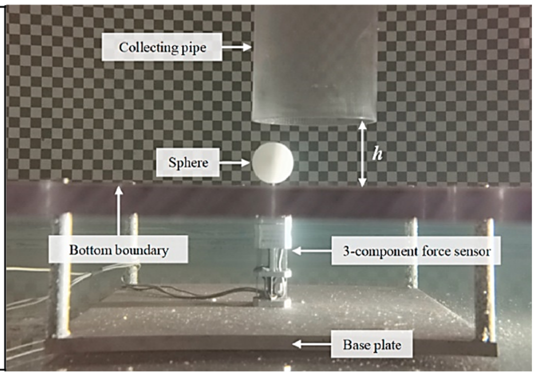


Figure 14. Research on characteristics of particle motion. (**a**) Mechanism of nodular particle elevation; (**b**) suction flow test (reproduced from [40], with permission from Elsevier, 2021).

4.2. Research of Impact Jet Mechanism

Impact jet is a key technical problem of double-row hydraulic sluicing collection technology. Changing the parameters of nozzle angle, flow rate, shape, etc., has an important impact on the collection efficiency of the device and the bottom material disturbance. Many scholars have studied impact jets.

Tian et al. [66] used experimental methods to study the impact pressure characteristics of high-speed submerged jets on baffles under different outflow velocities and different distances between baffles and spout. Perng et al. [67] studied the scouring effect of parameters such as moving speed and jet intensity on sand bed, and proposed the shallow flow theory of jet trenching process through experimental observation of water and sand movement. Ye et al. [68] carried out a numerical calculation of jet impact force and studied the influence of different jet distances on jet impact pressure, concluded that a nozzle with a diameter of 2 mm would produce the maximum jet impact pressure when the jet distance was 50 mm, and verified the effectiveness through experiments. Chen [69] conducted an in-depth analysis of the flow field characteristics and impact pressure of submerged impact jets and studied the effects of impact angle, impact height and Reynolds number on jet diffusion and the maximum pressure coefficient on the impact wall. Zhang et al. [70] used the Wray–Agarwal turbulence model and a PIV test to study the oblique submerged impact jet at different impact heights and concluded that the impact height affects the flow field structure of the oblique jet, while the range of effective impact pressure on the wall is independent of the impact height. Damien et al. [71] studied the erosion of a two-dimensional vertical impact jet on a horizontal sand bed, and concluded that under different impact distance and jet velocity conditions, the depth and width of the sand pit are determined by effective impact distance and dimensionless erosion parameters. At present, the mechanical research of impact jets is mainly carried out through the combination of simulation and experiment, which is conducive to promoting the development process of low-disturbance deep-sea mining equipment.

4.3. Research of Multi-Parameter Comprehensive Optimization

Considering that the performance of the collection head is closely related to the stable movement of the track and the overall size of the mining vehicle, the parameter optimization of a single structure is not comprehensive, and some scholars carry out the design optimization of the multi-objective parameters of the collection system.

In 2013, Lee et al. [72] designed an ore-collecting device based on the Coandă effect and conducted experiments with the nozzle bottom height, jet flow rate and travel speed as variables to test the collection efficiency of the device. At the same time, the MATLAB meta-model is used to carry out multidisciplinary design optimization on the parameters of the bottom height of the collection head, the curvature of the collection plate, the flow rate and the shape of the nozzle, etc. After optimization, the overall system meets the design constraints and reduces the power consumption by 14.1%. In 2019, Cho et al. [73] also explored the design optimization of the collection system under the constraint coupling relationship. This team designed a Coandă-effect-based collection device for the collection head and carried out a model test study on the collection efficiency. Five variables including nozzle configuration, collection plate radius, jet flow rate, nozzle off bottom height and collection head traveling speed were considered in the experiment. Then, a global optimization method based on Kriging random information is proposed, as shown in Figure 15. They combined the effects of buoyancy, control, collecting, transfer, driving system and chassis structure. The energy consumption of the optimized device is reduced by 20.43%.

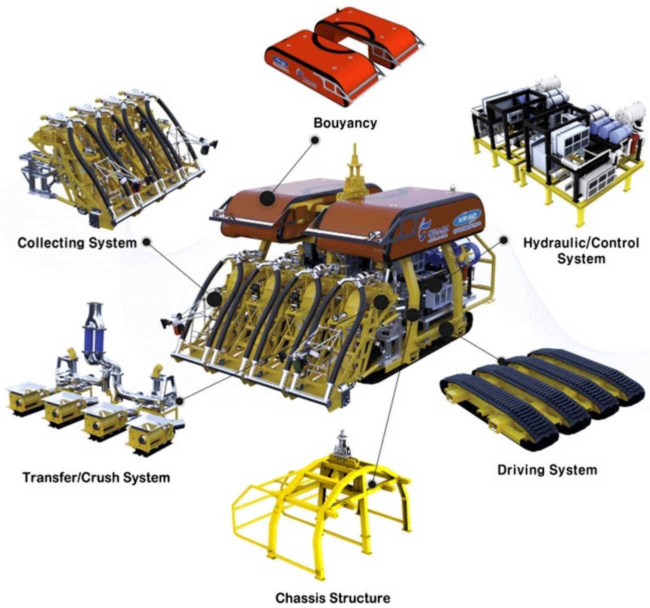


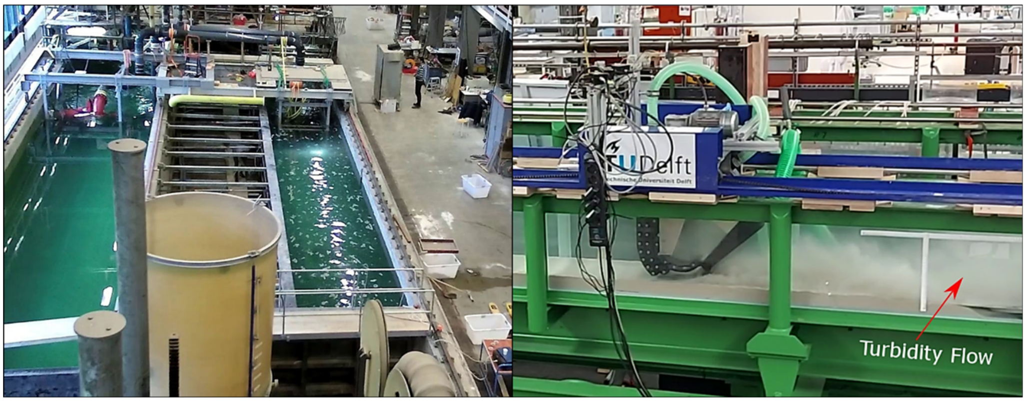
Figure 15. Multi-parameter optimization method for collection technology (reproduced from [73], with permission from Elsevier, 2019).

4.4. Research of Low Disturbance of Sediment and Deep-Sea Organisms

Due to hydraulic scour and suction, the hydraulic collection device will cause certain damage to the seabed bottom in the working process, which will further affect the seabed ecological environment. Some scholars have carried out a series of studies on the environmental disturbance performance of the collection device and the prospecting of deep-sea organisms while optimizing the structure of the collection device.

GSR conducted a detailed survey of the benthic biota in the CCZ and obtained that deep-sea bacteria and archaea comprise the majority of the organisms in the benthic environment, in addition to macrofauna such as Nematoda, Tanaidacea and Copepods [49]. They demonstrated that the biomass and abundance of organisms in the CCZ is low, about 1% of that in a typical continental shelf environment, but that the species diversity is high, with a large number of new species found in the samples. Therefore, there is still a need to focus on the impacts on organisms during the collection process [74,75]. In terms of sediment disturbance, Timm et al. [76] assessed the coverage of the plume by optical imaging with a camera at the square-kilometer scale and processed the static images using the CoMoNoD method, which can quantify the macroscopic impact of the plume. However, there is still a lack of research related to the quantification of suspended plumes Future improvements in automated image analysis capacity may reveal an even larger impacted area with unknown effects to the deep-sea habitat. Yue et al. [30] analyzed the performance of the collection head from the aspects of sedimentation efficiency and flow field disturbance through the method of combining numerical simulation and experiment, and concluded that the Coandă-effect-based collection head had low energy dissipation and small flow field disturbance, and had a good commercial application prospects. Li et al. [77] analyzed the effects of ore collection flow and drag velocity on the collection efficiency of the device, the turbulent kinetic energy of the ore collection flow field and the volume fraction of seawater sediment mixture, and simplified the sediment into a liquid with a density of 1400 kg/m^3 for simulating the diffusion process of sediment–seawater mixture. It is concluded that the disturbance to the near-bottom flow field of the Coandă-effect-based collection device is minimal under the same collection efficiency. Alhaddad et al. [34] proposed a Coandă-effect-based collection head with a flat bottom. The CFD method was used to optimize the structure of the collection head, and full-scale experiments were conducted to verify it, as shown in Figure 16a. In the experiment, four parameters of jet velocity, forward velocity, height off the bottom and bed type are studied on the collection efficiency of the collection head. The collection efficiency of the device is close to 100% when the jet flow rate is 10 m/s, the travel speed is 25 cm/s and the height off the bottom is 0 mm. At the same time, the team also conducted a study on the sediment disturbance characteristics of the collection head [78], and selected fine sand with a diameter of 0.145 mm to carry out the experiment in the absence of nodule particles, as shown in Figure 16b. It is concluded that the erosion depth of the sand bed is related to the flow rate, bottom clearance and traveling speed of the device. It is an important way to reduce the plume by reducing the erosion pressure of the jet on the sediment in a reasonable way and then reducing the water overflow at the back of the collection head. The study of low sediment disturbance is the key to realizing the commercial mining of hydraulic collection technology, which is mainly carried out through the combination of simulation and experiment. At present, experimental tests are mainly used, and there are few studies on sediment simulation, so it is necessary to further develop reliable sediment disturbance simulation studies.

At present, the important mechanism and key technology of hydraulic collection technology are mainly aimed at improving the collection efficiency of the collection head and reducing environmental disturbance, which is also the development trend of hydraulic collection technology in the future. In order to improve the collection efficiency, a new mechanism of particle stripping and lifting is expected to be proposed. In order to solve the problem of low disturbance of seabed sediment, it is necessary to deeply understand the flow field around the collection device and further optimize the design of the device structure.



(a) (b)

Figure 16. Experimental research of collection device. (**a**) Device structure parameter optimization (reproduced from [34], with permission from Elsevier, 2023); (**b**) research of sediment disturbance (reproduced from [78], with permission from MDPI, 2023).

5. Comparative Analysis, Research Difficulties and Prospects of Hydraulic Collection Technology

Through a large number of studies in the early stage, relatively mature hydraulic collection devices have been formed, including suck-up-based, Coandă-effect-based and double-row hydraulic sluicing collection device, but the collection efficiency, power consumption and structural parameters of each device are different. In order to further carry out a comprehensive evaluation of the performance of the hydraulic collection device and analyze the development trend of the hydraulic collection technology, this paper makes a comparative analysis of the performance characteristics of the hydraulic collection device, summarizes the relevant research on the hydraulic collection technology in recent years and the performance indicators of each device, puts forward an evaluation index of the design of the hydraulic collection head structure, and puts forward the prospect of the research on the hydraulic collection technology.

5.1. Comparative Analysis of Hydraulic Collection Technology

At present, scholars have conducted comparative studies on three hydraulic collection technologies. Yue et al. [30] built three kinds of collection head models according to sea test prototypes of different hydraulic collection methods. Under the condition that Froude numbers were similar and key parameters were the same as the proportions of the original models, the transverse width, bottom clearance and jet cross-section of the three models were set to be the same, and the collection performance of the three structures was analyzed by STARCCM+ (version 13.06) software. The collection performance of different structural models is analyzed from two aspects—collection efficiency and flow field disturbance—and the performance of three kinds of collection heads with a collection efficiency of 80% is evaluated. Among them, the energy consumption of the double-row hydraulic sluicing collection head is the least, and the flow field disturbance of the Coandă-effect-based collection head is the least. Li et al. [77] also adopted the above model and concluded that the moving speed has a great influence on the collection efficiency of the collection head, among which the moving speed of the Coandă-effect-based collection head has the least influence on the collection efficiency of the collection head.

In this paper, it is concluded by comparing the previous research that the suck-up-based collection device has a relatively simple structure, but it has problems such as low collection efficiency and high energy consumption. Coandă-effect-based collection device mainly produces pressure difference to promote nodules through the Coandă effect, which requires relatively large jet flow velocity and relatively high energy consumption, but has little geological erosion on sediments, which can significantly reduce environmental disturbance and play an obvious role in reducing plumes, and has been applied more maturely in sea trials in various countries [31,48,49]. The energy consumption of a double-row hydraulic sluicing collection device is relatively low, but the collection flow field is more complex, and the collection efficiency depends on the parameters of the collection head. At the same time, due to the presence of an impact jet, the device has a great disturbance and influence on the seabed [30]. Therefore, the Coandă-effect-based collection technology has lower energy consumption and less disturbance to the seabed environment, so it has a better application prospect. At the same time, considering that the research on hydraulic collection technology is mainly related to the research method, the change in the parameters of the device and the change in environmental parameters, this paper summarized the relevant research on hydraulic collection technology in recent years, taking the collection efficiency as the evaluation index, and sorted out in Table 2. The ✓ in the table indicates that the study conducted multiple sets of tests for the specified parameters and obtained multiple results.

Table 2. Recent research related to hydraulic collection technology.

Collection Head Structure	Author (Year)	Research Method	Bottom Height (mm)	Travel Speed (m/s)	Flow or Jet Velocity	Nodule Size (mm)	Sediment Selection	Collection Efficiency
Suck-up-based	Ziyu Yue (2021) [30]	Simulation and experiment	30	✓	✓	20	✓	✓
	Jingchao Hu (2020) [38]	Experiment	✓	—	✓	20	—	—
Double-row hydraulic sluicing	Jie Liu (2023) [53]	Simulation and experiment	100	0.5	✓	10–100	—	—
	Dongkuan Zhang (2022) [52]	Simulation	180	—	✓	—	—	—
	Lei Guan (2021) [37]	Half empirical and half theoretical method	180	0.6–0.8	✓	50–120	—	✓
	Ning Yang (2003) [51]	Experiment	✓	0–0.7	—	20–100	✓	✓
Coandă-effect-based	Qiang Yang (2023) [46]	Simulation	80	0.5	✓	60	—	✓
	Baiyuan Zhang (2023) [47]	Simulation and experiment	30	0.2	✓	20	—	✓
	Hao Jia (2022) [44]	Simulation	6	✓	✓	10	—	✓
	Jingchao Hu (2022) [27]	Experiment	30	0.45	✓	20	—	✓
	Alhaddad (2023) [34]	Simulation and experiment	20	✓	✓	8–80	✓	✓
	Ziyu Yue (2021) [30]	Simulation and experiment	30	✓	✓	20	✓	✓
Spiral suction disc type	Zihan Liu (2023) [55]	Experiment	15	0.2	✓	10	—	✓

Through the summary analysis, it is concluded that the main structural parameters in the current research process of hydraulic collection technology are the height off the bottom of the collection head, the forward speed, the suction flow (suck-up-based), and the nozzle flow (Coandă-effect-based, double-row hydraulic sluicing). These parameters have a great influence on the collection efficiency and should be given priority in the process of structural design optimization. At the same time, through sorting out and analyzing previous studies, this paper proposes a structural design evaluation index for the hydraulic collection head, as shown in Figure 17. The structure of a hydraulic collection head with good practicability needs to meet the three aspects of high collection efficiency, low environmental disturbance and low power consumption as much as possible. High collection efficiency is directly related to the output of the collection system, low power consumption can greatly improve the economy and commercial exploitation potential of the collection head, and low environmental disturbance can improve the environmental protection of the collection system and reduce the interference to the seabed environment. In the process of designing the structure of the hydraulic collection head, these three factors should be comprehensively considered, and the specific parameters of the collection head such as particle lifting mechanism, travel speed, flow rate, structure (size, height off the bottom, baffle shape, nozzle structure, nozzle angle) should be further studied.

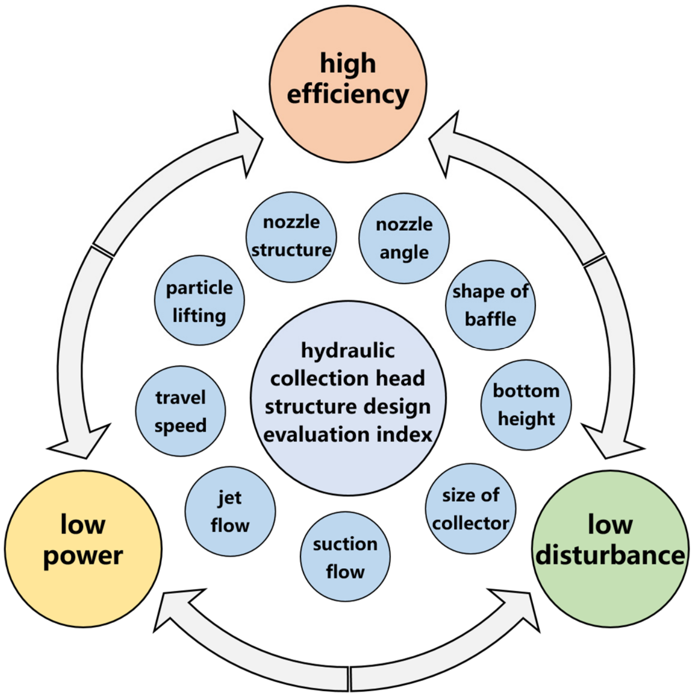


Figure 17. Hydraulic collection head structure design evaluation index.

5.2. Research Prospect of Hydraulic Collection Technology

Although a lot of research progress has been made on hydraulic collection technology, there are still large optimization spaces and challenges in the following aspects. First, the size of nodules used in the current study is generally relatively simple. Due to the complex size distribution of solid sea nodules, the selection of nodule size can be optimized in the study according to the particle size distribution curve of nodules in relevant sea areas, which can more accurately predict the collection efficiency of the device. Second, the disturbance of sediments is rarely considered in the current research, and the difficulty lies in the simulation of sediments and the setting of bottom material in the simulation process. In future studies, the sediment should be regarded as a suitable way of continuous phase or particle equality, and the interaction between ore particles and sediment should be considered. The appropriate sediment simulation and bottom material setting method should be selected, which has important reference value for seabed mining environment disturbance and device collection performance evaluation. Thirdly, the process simulation of collecting and lifting particles of the collecting head involves multi-scale problems, from the collecting head scale to ore particle scale to the sediment scale. There are at least three orders of magnitude differences, and coupling the three scales into a model for simulation operation is a difficulty in the current research. Fourthly, because the collection system is very complex and involves the influence of multiple parameters, the adoption of a multi-parameter parallel optimization method in the optimization design process is the key to comprehensively improving the performance of the collection head, and there is still little relevant research in this aspect.

6. Conclusions

In this paper, the resource distribution and physical characteristics of deep-sea polymetallic nodules are reviewed. First, the previous studies on the size and mass distribution of nodules are introduced, and then the current research status and key technologies of polymetallic nodule collection technology are introduced. The advantages and disadvantages of different hydraulic collection technologies are compared and analyzed, and the research prospects of hydraulic collection technologies are introduced. Finally, the following conclusions are drawn:

1. Among the existing collection methods, the hydraulic collection technology is more in line with the application prospect of commercial mining, in which the Coandă-effect-based structure has better relative performance, but it is also necessary to adapt to local conditions and select appropriate collection methods according to the specific environmental conditions of the seabed in the target sea area;
2. The bottom height, forward speed, suction flow (suck-up-based) and nozzle flow (Coandă-effect-based, double-row hydraulic sluicing) of the collection head have a great influence on the collection efficiency of the hydraulic collection head, which should be given priority in the design of the collection head structure. At the same time, the required flow of the collection head is directly related to the power consumption of the collection head, which is an important factor in evaluating the performance of the collection head. Through reasonable structural design, the flow of the collection head can be reduced as much as possible under the condition of the same collection efficiency, which can better improve the economy of the device;
3. At present, the performance of the collection head is mainly evaluated through the combination of simulation and experimental tests. This method verifies each other from two aspects and has high reliability, but there are still many difficult problems to be optimized and solved. First, in the simulation process, researchers generally use nodule particles of the same size, which do not have a high reference value for the real seabed environment. Nodule particles in the simulation process can be improved through the distribution curve of nodule particle size in relevant sea areas, so as to make the simulation results more reliable. Secondly, appropriate sediment simulation and sediment setting methods are selected to simulate the environmental disturbance of seabed mining. Thirdly, considering the multi-scale problem of collection device-ore particle-sediment, the multi-scale target is coupled to the same example for simulation;
4. In the structural design of the acquisition head, the main optimization goal is to reduce energy consumption as much as possible and reduce the disturbance to the seabed environment while ensuring a certain collection efficiency. Considering the complex structure of the collection system, the influence of other components in the collection system on the collection performance of the collection head should also be considered while studying the structure of the collection head separately, and the overall optimization of the collection head structure should be carried out through multi-parameters. At present, there is still a large space for the development of a collection system, and the new collection head structure and new collection methods are also the directions for further research and development of deep-sea mining in the future under the condition that the design purpose and demand are met.

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