Design and development of Underwater Pump-Suction Foreign Body Salvage Device for Nuclear Power Plant

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Abstract. Foreign matter entering the reactor system of a nuclear power plant will lead to the deterioration of the performance of the system equipment, make the operation of the equipment abnormal, and will lead to equipment damage and even affect the safety of the reactor in serious cases. The environment of the primary circuit of the nuclear power plant is radioactive, and when foreign matter enters the primary circuit, the traditional salvage method can not meet the need for radiation protection. In this paper, a foreign body salvage device is designed, which uses water as a shielding layer to retrieve underwater foreign bodies by pump-suctioning and realizes the convenient salvage of foreign bodies in the radioactive environment.

Keywords: Reactor, foreign matter, salvage, pump-suction

1 Introduction

There are three main sources of foreign bodies in nuclear power plants: first, foreign bodies that do not belong to the system and equipment of nuclear power plants; The second is the foreign matter that originally fell off the equipment of the nuclear power plant; Third, due to the operation of the nuclear power plant, the sediment of the working medium dissolved matter formed by precipitation[1]. The impact of foreign matter on nuclear power plants is mainly reflected in the following three points: First, security threats. If foreign matter in a nuclear power plant enters the core or primary circuit system, it may lead to damage to the fuel assembly cladding, increase the radiation level, and even cause the spread of radioactive pollution, which directly threatens the safe and stable operation of the nuclear power plant. Foreign objects can also damage system equipment, such as filters, chemical processors, etc., resulting in equipment failure and further aggravating safety risks. Second, operation obstacles. Foreign objects can block the flow of coolant and cause the nuclear reactor to overheat, affecting the normal operation of the nuclear power plant. Foreign matter attached to the surface of the fuel rods can cause the fuel rods to overheat and even cause the fuel rods to fail, increasing the risk of nuclear reactors. Third, Environmental pollution. The environment around a nuclear power plant is sensitive, and if a leak is caused by a foreign object, it may contaminate the surrounding environment, causing harm to the ecosystem and human health.

The common anti-foreign body measures in nuclear power plants are to establish a strict anti-foreign body mechanism, such as establishing a foreign body isolation area, controlling the number of openings in the system, and recording the number and status of items brought in. This kind of method can play an effective role in restricting foreign bodies, but it can not completely solve the consequences of foreign bodies caused by foreign bodies. And can not cope with the system equipment shedding and working fluid deposition of foreign bodies. However, the traditional salvage method can not meet the requirements of a nuclear power plant for foreign body salvage radiation protection [2]. In this paper, the foreign matter in the primary pressure vessel of the nuclear power plant is studied, and an underwater pump-suction device is developed to recover foreign matter with water as a shielding layer.

2 Application Objects and Research Status

2.1 Application Objects

In this paper, 14 foreign body incidents that occurred in 18 nuclear power units of four domestic nuclear power plants from 2020 to 2023 were investigated. The findings were as follows: 1. According to the source of foreign body, 13 foreign body incidents were caused by foreign body introduction, and 1 foreign body was deposited by system equipment; 2. According to the weight analysis of foreign bodies, the weight of foreign bodies in the 14 cases was all less than 1kg; 3. According to the location analysis of foreign bodies, 10 foreign bodies occurred in open containers, and 4 foreign bodies occurred in open pipes. Based on the above findings, the use scenario designed in this paper is the steel pressure vessel in the radioactive environment of the nuclear power plant, the reactor pressure vessel, the reactor main pipeline, and the spent fuel pool are the main use scenarios[3], and the foreign matter with a total weight of less than 1kg is the application object.

2.2 Research Status

Other common forms of foreign body grasping equipment in China mainly include air claw type and multi-functional special type, as shown in Figure 1. The air claw salvage tool simulates hand grip to grasp foreign bodies. Its advantages are simple to grasp foreign bodies, and foreign bodies are not easy to fall after grasp. The disadvantages are that it is difficult to grasp foreign bodies in thin gaskets, can only grasp foreign bodies in the vertical direction, and can not grasp foreign bodies on the side. In addition, most of the deposited foreign bodies formed by the precipitation of working fluid have a soft surface texture, which is prone to causing foreign bodies to be crushed during the grasping process, forming more small foreign bodies, so the air claw type cannot cope with such foreign bodies. The multi-functional special fishing tool is equipped with multiple grasping joints, such as fishhook type, strong magnetic type, and lasso type, which has the advantage of being suitable for different grasping scenarios. The disadvantage is that when applied to a radioactive environment, it will cause radioactive contamination of multiple grasping joints, and in the process of replacing grasping joints, personnel need to directly contact the grasping joints that may be contaminated by radioactivity, and the radioactive exposure risk of personnel is high[4].

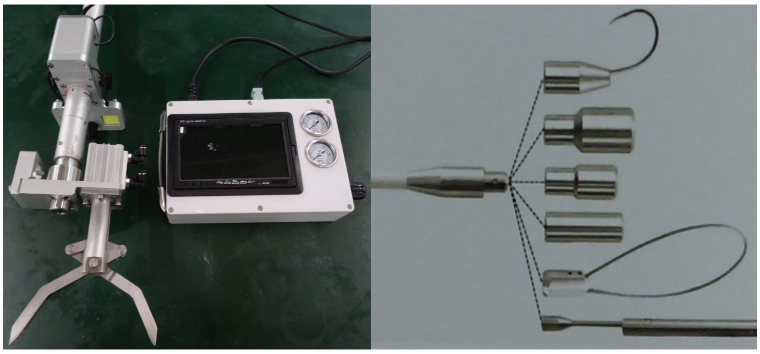

Fig. 1. Air claw fishing tool (left) and multi-function fishing tool (right).

3 Equipment Design

3.1 Overall Design

The overall structure of the underwater foreign body salvage device is shown in Figure 2. The underwater foreign body salvage device adopts the principle of pump-suctioning, and the foreign body can be sucked into the collection pipe when the collecting mouth is close to the underwater foreign body. The collection port is divided into straight pipe type and bent pipe type, which can pump-suction vertical direction (in the container) and lateral foreign matter (in the pipeline), respectively. Foreign body salvage and collection are completed underwater to avoid frequent water discharge. The equipment is designed to salvage foreign bodies with diameters of 0.5mm~50mm and weights less than 1kg in reactor pressure vessels and spent fuel pools.

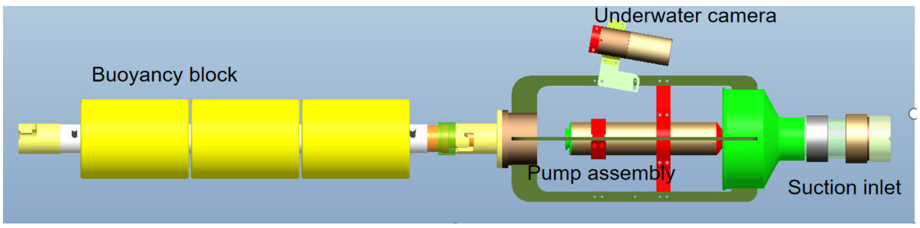

Fig. 2. Overall design.

3.2 Design of Pump-Suction Assembly

The salvage device realizes the capture and release of foreign bodies through the positive and negative rotation of the pump-suction assembly. Its geometric dimensions are shown in Figure 3, and its main parameters are shown in Table 1. The rear end of the pump-suction assembly is designed with a filter screen with a diameter of 0.5mm to ensure the fishing accuracy of the equipment. Since the pump-suction assembly is the core part of the equipment and it works in the underwater radioactive environment for a long time, the pump-suction assembly is designed to be sealed and radiation resistant. The outer surface of the main body of the pump-suction component is made of integrated aluminum alloy, and the outer shell, the blade end, and the tail end are sealed by an O-ring (outer seal). The inner surface of the main body of the pump-suction assembly is lined with a thin lead plate as the overall shielding material of the pump-suction assembly. The pump-suction motor, controller, encoder, and other components are placed inside the main body of the pump-suction assembly, and circular lead covers are designed at both ends to seal the main components of the pump-suction assembly (inner seal). The circular lead cover at the blade end is provided with a motor through the hole, and the through hole is sealed by a stuffing box. The circular lead cover at the tail end is provided with a wiring control port, and the wiring hole is provided with a static seal. The pump-suction motor shaft is connected to the blade shaft by a coupling placed at the blade end. The seal of the blade shaft is a magnetically coupled dynamic seal to ensure the sealing performance under long-term motion. The blades are made of stainless steel to ensure their long-term durability in underwater environments. The joint at the tail end is the only non-metal part of the pump-suction assembly that has been exposed to radioactivity for a long time[5]. According to research, the radiation resistance of polytetrafluoroethylene is good, and the tolerance dose is up to 100Mrad. Its dielectric constant and dielectric loss are low, and the electromagnetic shielding effect is good. Therefore, the end joint shell uses its shell material to choose polytetrafluoroethylene. In addition to the O-ring static sealing at the joint, the glue-filling process is also used to ensure the waterproof performance of the joint.

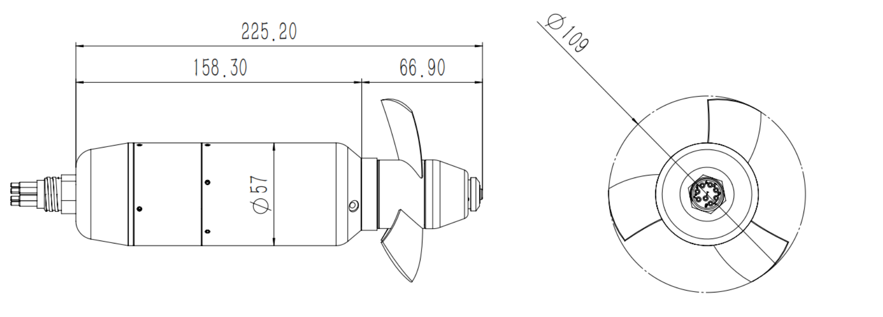

Fig. 3. Pump-suctioning size.

Table 1. Main parameters of pump-suctioning assembly.

Performance index	Parameter	Performance index	Parameter
Input power	580W	Working depth	0-850m
Rated voltage	48VDC	Weight	≤1.7Kg
Rated thrust	≥10kg	Blade material	Stainless steel
Seal construction	Magnetically coupled rotary seal	Signal power supply	12V±5%

3.3 Design of Auxiliary Tooling

Fig. 4. Control box and auxiliary tooling.

The design of auxiliary tooling includes the collection frame, control box, and installation tool, as shown in Figure 4. The underwater action of the equipment is controlled through the control box. One side of the panel of the control box is the display area, which is used to display the environment picture captured by the underwater environment camera and locate the relative position of the suction inlet and foreign matter, so as to facilitate suction operation. The control box is equipped with foreign object recognition software, which can identify common nuclear power plant foreign objects such as bolts and nuts. When such foreign objects are found in the environment camera, the software will automatically recognize them and give a prompt on the top right of the display screen. The underwater camera adopts an irradiation-resistant design, and its maximum irradiation dose rate is not less than 20Gy/h. The other side of the panel is the interface and pump-suction suction control area. The underwater camera connection interface and pump-suction suction assembly interface are provided in this area, both of which are used to control the salvage and release of foreign bodies of the equipment and adjust the suction output of the equipment. The collection frame is used to collect foreign bodies. When retrieving highly radioactive foreign bodies, the collection frame is placed in the water by the aerial crane. After the foreign matter is placed in the collection frame, the on-site personnel shall evacuate and place the foreign matter together with the collection frame into the prepared shielding container through the remote control aerial crane to avoid personnel's radioactive exposure.

3.4 Device Installation and On-Site Implementation

At the beginning of foreign body salvage, we first connect the video cable and submersible motor cable to the control box, connect the power supply of the control box, and then click the pump-suction assembly to confirm the successful connection of the equipment. The buoyancy block is connected to the salvage equipment to reduce the gravity of the equipment in the water, as shown in Figure 5. The carbon fiber long rod is connected to the buoyancy block, and the number of long rods is determined according to the water depth. The length of each long rod is 2m. Meanwhile, the foreign body collection frame is put into the pool through the safety rope. We turn on the power switch, determine the position of the foreign body through the camera, open the pump-suction assembly, and gradually adjust the motor speed, so that the foreign body pump-suction is sucked into the suction inlet and attached to the filter screen, and the filter screen can avoid foreign body with a diameter greater than 0.5mm into the blade wheel. We move the collection tube to the foreign body collection frame, stop or reverse the motor, and discharge the foreign body into the collection frame. After all foreign bodies are recovered, we turn off the pump-suction suction assembly, lift the foreign body salvage device and the foreign body collection frame off the water surface, and recover the equipment.

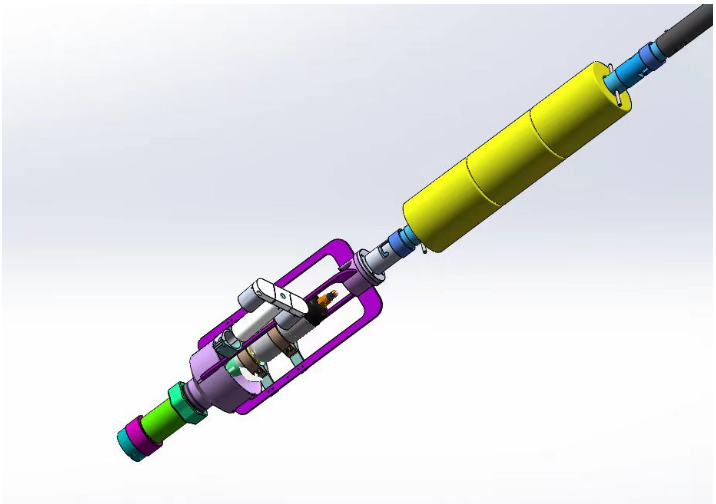

Fig. 5. Use renderings.

4 Performance Test

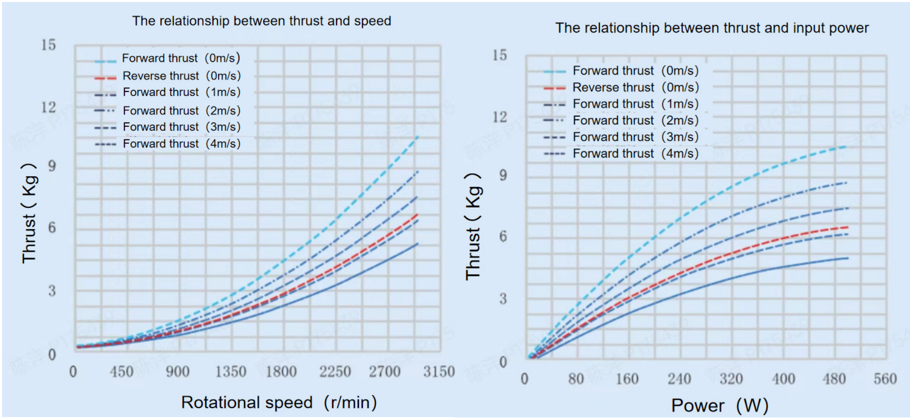

Fig. 6. Thrust speed curve (left) and thrust input power curve (right).

The positive and negative thrust of the pump-suction assembly is the key to realizing the salvage capability of the equipment. Because the water flow disturbance will affect the fishing capacity of the pump-suction assembly, when the water flow is opposite to the pump-suction direction, the pump-suction capacity will be weakened significantly. Therefore, this paper conducts rotational speed-thrust test and power-thrust test for the pump-suction assembly under different flow rates (0m/s, 1m/s, 2m/s, 3m/s, 4m/s). The test conditions are as follows: with the test water depth set at 1 meter underwater, we take inhalation as the positive direction, and the test position is close to the suction inlet. The test results are shown in Figure 6. According to the test results, as the speed increases, the output of the pump-suction assembly also increases, and the higher the speed, the greater the effect of the speed on the pump-suction output. The higher the input power of the pump-suction assembly, the higher the output of the pump-suction assembly, but the higher the power, the output increase caused by the increase of power is significantly reduced. From the test result diagram, taking the test curve in still water as an example, it can be found that when the power of the pump-suction component exceeds 400W, as the power is increased by 10%, the pump-suction output is increased by less than 8% and the value is less than 1kg. In this case, the influence of power on the pump-suction output is significantly reduced, and the pump-suction efficiency is significantly reduced. At this time, the corresponding pump-suction output is about 9.75N, and the speed is about 2800r/min. When the operating speed of the pump-suction assembly is above 2250r/min, the output of the pump-suction assembly begins to increase by more than 10% when the speed increases by 10%, and the output of the pump-suction assembly begins to be significantly affected by the speed increase. In this case, the output of the pump-suction group can meet the requirements of conventional fishing when the output of the pump-suction group is above 6kg, and the corresponding power is 240W. Therefore, the operating efficiency of the pump-suction assembly is the highest when the operating speed of the pump-suction assembly is 2250~2800r/min and the input power is 240~400W. In the actual operation test, influenced by many factors such as water flow rate and uneven adsorption, combined with historical experience, when the operating speed of the pump-suction component is controlled between 2400 and 2700r/min, the input power can be stable within the maximum operating efficiency interval, which is the actual optimal operating speed interval.

5 Engineering Applications

According to the test results under laboratory conditions, the equipment will be applied in domestic nuclear power plant A in 2023. This equipment can meet the requirements for effective salvage of foreign bodies within the design range in both laboratory environments and on-site use of nuclear power plants. The actual salvage situation is shown in figure. 7. However, in the actual application process, it is found that the salvage operation in the reactor pressure vessel of a nuclear power plant is inconvenient and inefficient due to the large height drop between the operation area and the water area where the foreign body is located. Field analysis shows that when the total length of the carbon fiber rod exceeds 10 meters, there will be obvious movement retardation in the process of retrieving foreign bodies. The reason for this hysteresis is that during the equipment design process, the designed buoyancy block can only balance the underwater gravity of the equipment body. Too many carbon fiber rods resulted in the equipment in the water part of the gravity being much greater than the original design buoyancy, resulting in the implementation of the salvage operators causing difficulties. On the other hand, because the carbon fiber long rod itself has a certain toughness and there is a gap in the connection position of the superimposed long rod, when the equipment is operated by the multi-heel long rod, part of the displacement is temporarily offset by the plastic deformation of the long rod, which causes the equipment to move hysterically under water. It is estimated that when the total length of the long pole exceeds 20 meters, the operator will find it difficult to operate the equipment for salvage operations.

Fig. 7. Foreign body salvage effect.

In view of the above situation, the equipment has developed a bridge tool, as shown in Figure 8, which is used for foreign body salvage when the height drop is more than 10 meters. The tool is usually used in conjunction with the bridge over the pool of the reactor pressure vessel in a nuclear power plant. The tool realizes the positioning in the north-south direction and the east-west direction by moving the pulley and the bridge, respectively, and realizes the positioning fine-tuning by the linear guide rail. The vertical height positioning is adjusted by the carbon fiber long rod, and the vertical height is fine-tuned by the worm gear. Through the pulley rolling on the bridge tool and the motor movement of the bridge instead of the original manual operation positioning, the restraint of the carbon fiber long rod is added, and the fishing efficiency of the fishing equipment in response to the high drop operation has been significantly improved. At the beginning of 2024, when the foreign body salvage work in the reactor pressure vessel pool of a domestic nuclear power plant B was carried out (the actual height drop is about 15 meters), by using the bridge tool, the actual construction period was saved by 1 man-hour/person, the work efficiency was improved by nearly 25%, and the collective radiation dose of personnel was reduced by 1mSv in a single salvage.

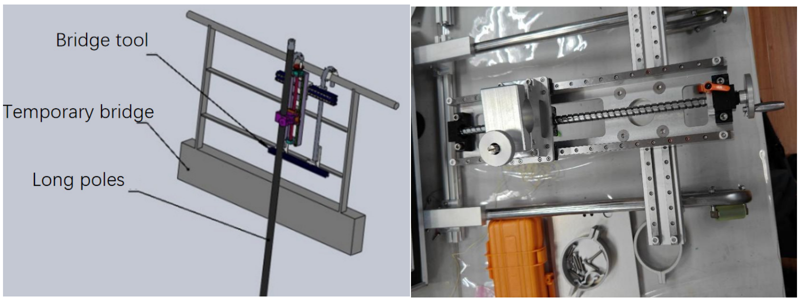

Fig. 8. Bridge tool effect drawing (left) and physical drawing.

6 Conclusion

In this paper, a foreign body salvage device is designed to achieve the salvage of foreign bodies inside containers and pipelines under the condition of meeting the requirements of personnel's reflective protection. The salvage capability can meet the salvage requirements of common radioactive foreign bodies in nuclear power plants and provide a special bridge tool to improve the applicability of the equipment in nuclear power plants when the salvage operation is carried out with a large height drop. This study provides a useful solution for the disposal of underwater foreign bodies in nuclear power plants. However, in practical application, on the one hand, there are many uncertain factors in the process of foreign body salvage, such as the type and location of the foreign body, which can easily affect the efficiency of foreign body retrieval. On the other hand, even if there is water as a shielding layer during the actual operation, there is still a small amount of radioactivity in the working environment of personnel. Therefore, improving the remote control of equipment to limit the exposure dose of personnel and improve the grasping efficiency of equipment is the future research direction of this subject.

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