Automatic sealing technology for solidification line of medium and low level radioactive waste in nuclear powered ships

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Abstract. The disposal of medium and low level radioactive waste in nuclear powered ships is increasing day by day. With the increasing requirements for nuclear safety and personnel protection, the intelligent disposal equipment should be improved to fully replace manual operations. The automatic capping technology in this paper can completely replace the original manipulator operation. With it, people can be kept away from dangerous working environments, thereby reducing the dose levels of the general population. The input of the device can also improve the safety and reliability of the whole operation line, thus improving the nuclear safety level of the solidification line.

1. Introduction
With a large number of nuclear powered ships have been put into use, their nuclear-powered devices will inevitably produce a certain amount of nuclear waste after long-term operation. How to dispose of nuclear waste in a safer and more scientific way has become an urgent issue. At present, nuclear waste is solidified and stored in special temporary storage places all over the world and transported to permanent storage areas within a certain period of time. Every link in this work is related to nuclear safety. In recent years, the disposal of nuclear waste in various fields in China is roughly divided into the following two forms: 1) For high-level radioactive waste, cooling, dry storage, disposal and recycling or deep underground burial can be adopted. 2) For the medium and low level radioactive nuclear waste, it is usually put into different types of metal barrels after solidification treatment, and buried shallowly for preservation.

2. Necessity of automatic capping technology
For the three waste treatment sites of nuclear powered ships, the medium and low-level radioactive waste is mainly composed of concentrated liquid and waste resin, which is mainly treated by cement solidification.

Cement curing (Figure 1) refers to the process of mixing medium and low level radioactive wastes referred to above into cement-based materials to form a solidified body. The purpose of cement solidification is to turn the fluidity and dispersion of waste into an integral solidified body suitable for loading and unloading, transportation and temporary storage, and the performance meets the disposal requirements. Cement curing mainly involves the consolidation of wastes in the solidified body in the form of physical inclusion.
Figure 1 Composition of low radioactivity solidification line in a nuclear-powered ship

Cement curing equipment mainly includes: cement feeding and mixing device, automatic capping system, roller system and control system. Among them, the cement feeding and mixing system is mainly used for cement solidification processing process, the automatic capping system focuses on opening and sealing the steel drums with low and medium radiation storage, and the roller table system mainly plays the role of transporting and conveying the solidified drums on the operation line. The above production links belong to the red zone, must avoid direct contact with personnel, need to have high intelligence and high reliability. In particular, the automatic capping system is one of the most complex systems, which involves tightening or loosening the bolts for the capping of the solidified barrel, and removing or capping the barrel lid and other complex actions. The process design of the existing curing line capping station requires the operator to complete the capping operation with the help of manipulator, electric impact wrench, positioning pin and magnetic spinner in the capping station. The technology of the system is backward, the operation procedure is complex, the work efficiency is low, the operation process of the staff is subjected to certain radiation hazards; The system runs for a long time, the accuracy of the manipulator and the reliability of the magnetic spinner are reduced to different degrees, and there are hidden dangers of nuclear safety. Therefore, in order to reduce the exposure dose of personnel and meet the needs of subsequent operation, the following automatic sealing system is specially designed.

3. The composition and working principle of automatic capping system

3.1. The composition of automatic capping system

The automatic capping system (as shown in Figure 2) is mainly composed of the executive part, the control part and the transmission part. The executive part is mainly used to execute the action instructions issued by the control part and realize the corresponding action of the equipment. The control part is mainly used for remote operation and monitoring of equipment, and for signal processing and output.

Figure 2 Composition of automatic capping system
1) The executive part is mainly composed of four parts: bearing beam, lifting assembly, adaptive platform and solidified barrel cover disassembly and assembly actuator. The load-bearing beam (as shown in Figure 3) is mainly composed of a beam and a fixed foot, which plays a load-bearing role in the whole execution part. The finite element mechanical analysis is emphatically carried out. Lifting assembly (as shown in Figure 4) is mainly composed of power unit, reducer and lifting assembly. Lifting assembly is mainly used for lifting the barrel cover dismantling assembly. Lifting components are integrated products, with lifting and rigid guide functions, and integrated upper and lower limit switches to ensure the safety of the equipment.

![Image of load-bearing beam](image)

**Figure 3** Structural composition and mechanical analysis of load-bearing beam

The adaptive platform (as shown in Fig. 5) is mainly composed of an upper flange, a linear motion system, a transfer flange, a lower flange and a limit plate. The adaptive platform has the functions of X and Y double degrees of freedom adaptive adjustment and automatic reset. It mainly realizes the self-adaptive alignment between the barrel cover assembly and the steel barrel. The solidified barrel cover disassembly and installation actuator (as shown in Figure 6) is mainly composed of bolt disassembly power unit, rotating disc, screw hole detection sensor, electromagnetic sucker, tightening assembly, conical positioning wheel, bolt detection sensor, power unit and rotation unit. The solidified barrel cover disassembly actuator has the functions of circumferential rotation, bolt and barrel cover disassembly and conical positioning wheel positioning, which mainly realizes the positioning alignment between the rotating plate and steel barrel, bolt and barrel cover disassembly. The curing barrel disassembly and assembly actuator is also provided with three groups of electromagnetic suckers, which generate magnetic field to adsorb and solidify the barrel cover after passing the current, and can realize the separation and sealing of the solidified barrel cover.
The control part is mainly composed of the monitoring system, the operation panel, the box body and the programmable logic control system. The integrated design concept is adopted to integrate the monitoring and electric cabinet into one, so as to realize the integrated design and reduce the space occupation of the control room. The control part communicates by means of fieldbus and its main function is to realize remote operation and monitoring of the equipment. Monitoring system adopts Siemens, Schneider or ABB equivalent brand monitoring panel. The main function is to realize the man-machine interaction between the staff and the equipment, and to realize the remote monitoring of the equipment. Programmable logic control system is mainly composed of terminal bar, programmable logic controller, driver, relay and transformer and other electrical components. Programmable logic control system is the control center of equipment, mainly including terminal bar, programmable logic controller, driver, relay and transformer, etc. Its main function is to realize the logic control of equipment, and to ensure the reliability of equipment operation.

The transmission part mainly includes power cable and signal cable (as shown in Fig.7). The power cable is mainly used to provide power to the equipment, and the signal cable is mainly used for signal transmission between the control part and the mechanical part. The connecting cable between the control part and the mechanical part passes through the hole through the wall after dismantling the component manipulator. The sealing steel plate and the cable waterproof joint are used to ensure the sealing of the hole through the wall, so as to ensure the negative pressure environment of the steel barrel capping room.
3.2. Working principle of automatic capping system

The goal of all actions of the automatic capping system is to loosen the fastener on the cover of the cement solidified drum. Lift the lid or close the lid and tighten the fastener. The total height of the cement solidified barrel is 1.5m, which is used to store various radioactive nuclear wastes. The cover of the barrel and the solidified barrel are connected by 8 bolts. In order to loosen and tighten the barrel cover fasteners in the target, the actuator of the automatic capping system has the movement function of four degrees of freedom: three degrees of freedom in the three-dimensional coordinate movement and one degree of freedom in the rotation movement of the actuator. In order to meet the target to be able to perform part of the project to bolt or screw hole position, fetch the execution of the block system components on the set screw hole detection sensor and bolt detection sensor, through the sensor parts and bolts or the relative position of threaded hole and transmitted to the control system, to adjust the drive power unit. In order to achieve the goal of being able to separate the solidified barrel cover from the barrel, the electromagnetic sucker of the executive part is put into work, and the solidified barrel cover is sucked up and moved to the side. In order to achieve the goal of combining the solidified barrel cover with the barrel, the actuating unit first moves the barrel cover to the solidified barrel joint position and removes the sucker to separate the barrel cover from it.

In order to realize the above functions, each module of the control system (as shown in Fig.8) undertakes its own tasks, including monitoring panel, power operation, positioning system, communication control, etc.

4. Key technologies of automatic capping system

There are two key technologies in the automatic capping system of low radioactivity solidified storage drums in nuclear powered ships. The first is the automatic induction tightening device technology, and the other is the laser positioning technology. The technical core of automatic induction tightening device is mainly divided into two parts: one is the analysis and calculation of tightening torque; The second is the control and action of tightening torque. Laser positioning technology is mainly based on the relative
of laser transmission and reception to accurately judge the relative position of the transmitter and the target.

4.1. Automatic induction tightening device technology

The opening and closing of the solidified barrel cover first needs to tighten and loosen the bolt connecting the solidified barrel cover and the barrel. This action needs to be automated, so automatic bolt tightening system is set up on the automatic capping device. In this case, the pretightening and tightening control of the capping bolt of the solidified barrel is the key technology of the entire capping automation device, which determines the effect of the barrel lid on the storage of nuclear waste materials, and also affects the nuclear safety of storage and transportation. The technology includes two key points: pretightening torque of sealing bolt and tightening control of sealing bolt.

4.1.1. The pretightening torque of the sealing bolt was analyzed

Bolt preloading analysis is the premise of the normal operation of the capping system. The maximum preloading force is:

\[ F_{\text{max}} = 3(1 - \xi)\pi d_1^2 \left[ \sigma \right] \left[ \frac{1}{16}(1 + \xi) \right] \]  \hspace{1cm} (1)

Tightening torque calculated by pretightening force is:

\[ T_1 = Fd_2 \tan(\psi + \rho)/2 \]  \hspace{1cm} (2)

The contact surface of the nut of the solidified barrel bolt and the tightening device is regarded as the same outer diameter, then the friction torque of the non-running-in contact surface is:

\[ T_2 = \mu_n F \left( D_1^3 - D_0^3 \right) \left( \frac{3}{2} \left( D_1^3 - D_0^3 \right) \right) \]  \hspace{1cm} (3)

Then the tightening torque is:

\[ T = T_1 + T_2 = F \left( \frac{p}{2\pi} + \frac{\mu \rho}{\cos \beta} + \mu_n r_n \right) \]  \hspace{1cm} (4)

Where: \( \psi \) - rising Angle; \( \mu \) - friction coefficient of screw pair; \( \beta \) - dental angle of axial Section; \( \mu_n \) - friction coefficient of support surface; Equivalent friction radius of torus - \( \left( D_1^3 - D_0^3 \right) \left[ \frac{3}{2} \left( D_1^3 - D_0^3 \right) \right] \)

4.1.2. Tightening control analysis of sealing bolt

The key to the analysis of sealing tightening control is the process monitoring. The automatic control of fastener tightening process can be achieved by Angle monitoring and torque monitoring and their combination.

First, by comparing the actual tightening process of fasteners, the important positions and parameter characteristics of the tightening stage are analyzed, as follows:

1) Pre-tightening torque, the final torque of fastener tightening;
2) Slow-release torque, which is the Angle starting point in the angle-torque detection method, is set as 20%-30% of the pretightening torque;
3) Torque upper limit, the torque after fastener pretightening is not greater than it;
4) The lower limit of torque, the torque after fastener pretightening should be greater than it;
5) Pretightening Angle, as the corresponding Angle of pretightening.
6) Angle upper limit and angle lower limit, fastener pretightening Angle range, more than its range is considered failure;

7) The maximum and minimum number of screw threads shall be within the range of the number of turning turns during tightening;

8) The upper and lower limits of time and the time of fastening process should not be beyond the range.

The surface described above controls the pretightening process and detects the tightening effect. The loosening of bolts is mainly controlled by Angle, that is, the loosening effect is controlled by the maximum and minimum thread number range and time range.

The angle-torque method is mainly used to control the relative rotation of fasteners in the whole process of fastener pretightening. Meanwhile, torque monitoring sensor is used to monitor the change of tightening torque in real time. By this method, the initial position of Angle control is determined as the premise of angle-torque method. After the initial position is passed, the special tool begins to calculate the angular travel. Set the travel to 90° and stop the action when the target is reached. In the next stage, pretightening is carried out at a relatively slow angular velocity and the change of tightening torque is monitored throughout the whole process. If the pre-tightening force is too small, it means that the heat treatment effect of the fastener is not good or the tensile strength of the material is too low; On the contrary, too much preload means that the hardness of the fastener after heat treatment is too high or the tensile strength of the material is too high, so as to achieve the purpose of monitoring the quality of the material.

On the tightening control of automatic capping system, angle-torque method is selected to control the whole process, mainly monitoring the change of torque, so as to combine torque with Angle. During the review, it is necessary to compare the theoretical tightening curve with the data collected in practice to confirm the accuracy of the whole tightening control.

4.2. Analysis of laser positioning technology

Laser positioning should be completed before the tightening device of the automatic working system of sealing fasteners is worked. The laser is located by distance measurement and determines the relative position of the target and the light source according to the Angle of its light. The success or failure of laser positioning is the key to the normal operation of the automatic working system of sealing fasteners.

The positioning process of the automatic working system for sealing fasteners is divided into two steps. The first step is to ensure that the center line of the executive part of the whole system is coaxial with the center line of the solidified barrel. Step 2: The center line of each of the 8 tightening devices needs to be coaxial to the center line of the fasteners on the curing barrel.

![Laser positioning sensor layout](image)

Figure 10 Laser positioning sensor layout

The whole device is equipped with 4 laser positioning probes, respectively numbered as: L, and, which are arranged in the circumferential direction. Wherein the vertical arrangement is in the same horizontal plane as the probe. When the center line of the executive part and the center line of the curing barrel
move to the coaxial state, the lifting assembly mechanism adjusts the overall height of the executive part to a predetermined position. When the fastener is released, the rotating unit is rotated to make the rotating disc drive the bolt fastening system to rotate, and the laser sensor scans the bolt position. When the fastener is rotated clockwise once over the rotation Angle, and then counterclockwise, the position of the scanned fastener is. To ensure that a single tightening device of the bolt fastening system is coaxial with the corresponding fastener. When the fasteners need to be tightened, the laser sensor is mainly used to scan the threaded holes of the solidified barrel. Bolt positioning is achieved through the above turning Angle.

5. summary
This paper first introduces the increasing number of nuclear powered ships and the generation of more and more nuclear waste, its disposal has become a problem that needs special attention at present. Then, the necessity and function of automatic capping system are analyzed for the disposal of medium and low radioactive nuclear waste. The application of this system can effectively reduce the exposure dose of human. In this paper, the composition and working principle of the system are introduced in detail. At last, two key technologies of automatic induction device tightening technology and laser positioning technology for automatic capping system are emphasized. In this paper, the technology and principle of automatic capping system are described comprehensively and in detail.

Acknowledgements
This project was financially supported by a research institute project: "Development of automatic capping device for solidification line of middle and low level radioactive nuclear waste".

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