The New Sealing Structure Design and Research of Pressure Hull of CRDM With the Special Environmental Conditions

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Abstract. The pressure shell seal structure is an important part of the control rod drive mechanism, and it is also one of the key structures to ensure the normal operation, safety and reliability of the reactor. In this paper, a new type of sealing structure of pressure shell of control rod drive mechanism is proposed to meet the requirements of multiple loading and unloading in special marine environment. Compared with the traditional welding connection structure, it has the advantages of fast and convenient operation, easy replacement of sealing components and so on. It can greatly shorten the loading and unloading time of control rod drive mechanism in the refueling process and avoid damage.

1. Introduction

Nuclear energy is a kind of clean energy with great development potential. Because of its advantages of economy, environmental protection, high efficiency and sustainable development, it plays an important role in the optimization of national energy structure and energy security. The development of nuclear energy is also of great strategic significance in national security. Nuclear energy is widely used in many fields, such as energy, ship, space, agriculture, medical treatment, environmental protection and scientific research. The successful development and application of marine nuclear energy meet the urgent needs of China's national strategy and the rapid development of China's marine economy [1-2].

The control rod drive mechanism (CRDM) is an important part of the nuclear reactor, which is an important action component to ensure the safety and controllability of the reactor. It undertakes the important tasks such as the start-up and shut-down of the reactor, the power regulation of the reactor core and the fast shutdown in case of accident [3]. The reactor CRDM under special marine environment should not only meet the requirements of fast and flexible power regulation, shock resistance, swing resistance, high temperature, high pressure and radiation resistance [4], but also meet the special requirements of multiple loading and unloading during the life of the reactor.

In order to effectively reduce the refueling cost and improve the operation economy of marine nuclear power, this paper proposes a new type of detachable sealing structure of pressure shell of control drive mechanism under special marine environment. Compared with the original traditional welding structure, it has the advantages of fast and convenient operation, simple operation, easy replacement of sealing components, and can greatly shorten the service life of control rod drive mechanism. This structural scheme has significant advantages in realizing multiple core refuelling and reducing economic cost.
2. Analysis of welding characteristics of traditional CRDM pressure shell

The traditional connection mode of CRDM pressure shell and penetration socket of pressure vessel head cover adopts trapezoidal thread and Ω seal welding structure (as shown in Figure 1). Under the conditions of high temperature, high pressure and radiation irradiation, the material of Ω welding parts cannot meet the requirements of repeated welding, cutting and rewelding process.

In order to improve the operation economy and reduce the refuelling cost under the special marine environment conditions, it is required that the operation time of reaction stack at full power should be as long as possible, and the single refuelling time should be as short as possible. In the whole design life of the reactor, it is necessary to carry out dozens of single component loading and unloading operations. Therefore, it is necessary to develop the CRDM pressure shell sealing structure with fast loading and unloading, simple operation and repeated use. This paper puts forward an urgent demand.

3. Sealing structure design of new type CRDM pressure housing

3.1. Composition of new sealing structure

The new seal structure of CRDM pressure hull suitable for marine environment is self-tightening seal structure, including two schemes: the seal structure without trapezoidal thread connection between CRDM pressure hull and reactor pressure vessel penetration (as shown in Figure 2) and the seal structure with trapezoidal thread connection (as shown in Figure 3). The seal assembly compresses the pressure housing, and the compression nut bears the axial thrust and seal preload; the seal structure with trapezoidal connection bears the axial thrust through the trapezoidal nut at the bottom of CRDM pressure housing, and provides the seal preload through the compression nut. They all realize the mechanical locking of the compression nut by setting the jacking screw in the radial direction of the compression nut.
The new seal structure is mainly composed of CRDM pressure shell, compression nut, seal assembly, compression nut and locking screw and pressure vessel top cover penetration. Among them, the structural performance of the seal assembly is the core component to realize the structural sealing function, which is mainly composed of the seal assembly compression sleeve, inner ring graphite seal ring, outer ring graphite seal ring, graphite carrier ring and connecting pin (as shown in Figure 4).

![Figure 3](image1)

**Figure 3.** Schematic diagram of new seal structure (with trapezoidal thread)

![Figure 4](image2)

**Figure 4.** Schematic diagram of sealing components of new sealing structure

The two schemes in Fig. 2 and Fig. 3 are self-tightening seal structure design. During the operation of the reactor, with the increase of the pressure of the core cooling medium, the axial upward load generated by the medium forms a bottom-up self-tightening stress on the seal assembly. During the increase of the medium stress, the self-tightening stress also increases synchronously and linearly, which further improves the CRDM resistance based on the initial sealing stress. The reliability of the new structure seal of the pressure shell is improved.

### 3.2. Main design parameters of new sealing structure

The main structural parameters of CRDM pressure housing new seal (with trapezoidal thread) are shown in Table 1, and the specific structural design is shown in Figure 5.
Table 1. The main dimension parameters of new sealing structure of pressure hull of CRDM

| NO. | Parts                                                   | Company | Parameter |
|-----|---------------------------------------------------------|---------|-----------|
| 1   | Design pressure                                        | MPa     | 17.2      |
| 2   | Design temperature                                     | °C      | 350       |
| 3   | Outer diameter of compression nut                       | mm      | 203       |
| 4   | Thread size of compression nut                          | mm      | Tr180×6   |
| 5   | Thread size of pressure housing                         | mm      | Tr140×4   |
| 6   | Thread height of pressure housing                       | mm      | 24        |
| 7   | Inner / outer diameter of inner ring graphite sealing ring | mm      | φ115/φ125 |
| 8   | Inner / outer diameter of outer ring graphite sealing ring | mm      | φ137/φ147 |

Figure 5. Profile of new sealing structure

3.3. Material selection and pressure check of new sealing structure

The new sealing structure of CRDM pressure vessel shell is made of SA182m F321. The sealing material is flexible nuclear grade graphite and the compression nut is ASME B1.5 ACME thread. In Figure 5, the trapezoidal thread of CRDM pressure shell and reactor pressure vessel penetration is Tr140×4 mm, and the height is 24 mm; the material of compression sleeve, graphite seal ring and connecting pin in seal assembly is austenitic stainless steel.

In the strength check of trapezoidal thread, when the temperature is 350 °C, the allowable stress of high alloy pipe is 111.0MPa (GB150.2-2011). The strength check calculation results of trapezoidal thread are shown in Table 2.
Table 2. Pressure calculation of trapezoidal thread of pressure shell and penetration

| NO. | Parts                                             | Company | Parameter |
|-----|--------------------------------------------------|---------|-----------|
| 1   | Thread top clearance Y                           | mm      | 0.25      |
| 2   | Screw diameter d                                 | mm      | 140       |
| 3   | Maximum axial load boundary                      | mm      | 115       |
| 4   | Maximum axial load Fmax                          | N       | 178564    |
| 5   | Base width of trapezoidal thread b               | mm      | 2.67      |
| 6   | Trapezoidal thread height p                      |         | 4         |
| 7   | Rotation number Z = H / P                        |         | 5.875     |
| 8   | Calculation of shear strength: τ                 | MPa     | 25.8      |
| 9   | Allowable stress [σ] 350                         | MPa     | 111.0     |
| 10  | Plastic material: [τ] = (0.6-0.8) [σ]             | MPa     | 66.6      |
|     | τ≤[τ] Qualified                                  |         |           |

Through the analysis of the calculation results, it can be seen that under the given operating environment, the strength of the trapezoidal thread connecting the pressure shell and the penetration meets the requirements.

The main performance index requirements of CRDM pressure housing seal assembly are shown in Table 3, and the relevant performance index requirements of graphite ring material in seal assembly are shown in Table 4.

Table 3. Main performance indexes of CRDM pressure housing seal assembly

| NO. | Parts                                             | Company | Parameter |
|-----|--------------------------------------------------|---------|-----------|
| 1   | Graphite ring density                            | g/cm^3  | 1.5~1.6   |
| 2   | Compression ratio of graphite ring               | %       | 10~25     |
| 3   | Rebound rate of graphite ring                    | %       | ≥35       |
| 4   | Stress relaxation rate of graphite ring          | %       | <10       |
| 5   | Thermogravimetric analysis of graphite ring (350 ℃) | %     | ≤0.1      |
| 6   | Leakage rate of sealing components               | Pa.m^3/s| ≤1.0E-06  |

Table 4. Main performance indexes of graphite ring plate for sealing assembly

| NO. | Parts                                             | Company | Parameter |
|-----|--------------------------------------------------|---------|-----------|
| 1   | Density                                          | g/cm^3  | 1.0±0.05  |
| 2   | Tensile strength                                 | MPa     | ≥4.5      |
| 3   | Compression ratio                                | %       | ≥41       |
| 4   | Rebound rate                                     | %       | <12       |
| 5   | Thermogravimetry (450 ℃)                         | %       | ≤0.5      |

4. Performance analysis of new type CRDM pressure housing seal structure

4.1. Meshing.
The self tightening stress boundary of the two schemes in Fig. 2 and Fig. 3 is different. The self tightening stress boundary of the scheme without trapezoidal thread is the circular surface of the outer diameter of the outer graphite sealing ring (i.e. φ 147 in Fig. 5). The self tightening stress boundary of the scheme with trapezoidal thread is the circular surface of the inner diameter of the inner sealing ring (i.e. φ 115 in Fig. 5) and the outer diameter of the outer graphite sealing ring (i.e. φ 147 in Fig. 5). The
self tightening stress of the two schemes varies with the medium pressure. The force curves are shown in Fig. 6 and Fig. 7.

**Figure 6.** Self-tightening force versus medium pressure (No trapezoidal thread)

**Figure 7.** Self tightening force versus medium pressure (With trapezoidal thread)

It can be seen from Fig. 6 and Fig. 7 that under the condition of the same stress change of reactor cooling medium, the ratio of self tightening stress is the ratio of stress boundary area of self tightening seal; the self tightening stress of the seal structure without trapezoidal thread is 2.57 times of that of the seal structure with trapezoidal thread, which is larger than that of the new seal structure without trapezoidal thread.

4.2. **Strength check of minimum wall thickness of penetration**

The minimum wall thickness design value of the new sealing structure penetration in Fig. 2 and Fig. 3 is 15.5mm, the penetration material is S32168, the inner diameter is φ147, the design pressure is 17.2MPa, the welding coefficient is 1, and the allowable stress at the design temperature of 350 ℃ is 94 MPa (according to the requirements of GB150, the allowable stress has considered the welding joint system of 0.85, because there is no welding requirement at the minimum wall thickness of the penetration according to the requirements of GB 150.3-2011, the wall thickness of penetration cylinder is calculated, and it is concluded that the wall thickness of penetration cylinder meeting the requirements of allowable stress is \( \delta = 14.8 \text{mm} < 15.5 \text{mm} \). The calculation results show that the minimum design wall thickness of penetration meets the requirements.
4.3. Performance analysis of compression nut thread of seal assembly

According to the practical experience of nuclear power plant, acme thread is selected as the compression nut of the new CRDM pressure shell seal structure. The thread structure is filled on the "thermal hydraulic test bench for nuclear grade seals of PWR nuclear power plant" of "nuclear grade static seal Laboratory of national nuclear power plant nuclear grade equipment R & D center" in Baohua, Suzhou, according to the operation conditions of the primary loop system of onshore nuclear power reactor The results are verified by experiments. The test medium pressure is 15.5MPa, the maximum temperature is 345 ℃, and the number of cycles is 16. The temperature rise and fall rate of each cycle is greater than 56 ℃/ h (the average heating rate is 76.6 ℃ / h, and the average cooling rate is 141.9 ℃/ h).

The test results show that the thread is free from loosening, jamming and other phenomena, and the thread teeth are intact and undamaged.

In order to further improve the safety of the compression nut and prevent the compression nut from loosening during operation, the jacking screw is set in the radial direction of the compression nut to realize mechanical anti loosening (as shown in Fig. 2 and Fig. 3).

4.4. Analysis of the influence of rolling condition on structural sealing performance

Under the special marine environment, affected by the tilt and swing of the hull platform, in order to prevent the relative swing between the pressure hull and the sealing structure of the penetration, the CRDM is fixed through the reactor top structure to make the pressure hull and the penetration and related components swing or tilt synchronously, so that the maximum swing amplitude at the top of the pressure hull is 4mm, and the maximum left-right swing at the sealing ring of the new structure sealing assembly is 4mm. The dynamic range is 0.05mm. Under the excellent rebound performance of the seal ring of the seal assembly, the swing will not cause the seal failure and can be approximately ignored.

4.5. Comparative analysis of two sealing self tightening structure schemes

The sealing structure without trapezoidal thread connection and the sealing structure with trapezoidal thread connection of CRDM pressure shell and reactor pressure vessel penetration are comprehensively analyzed:

1) In the seal structure without trapezoidal thread, the compression nut directly provides the axial thrust to resist the reactor cooling medium and the compression force of the seal assembly, while the compression nut with trapezoidal thread only provides the compression force, so the structural strength is safer. At the same time, the sealing nut can provide the thrust to resist the medium under unusual circumstances, which can be used as the second safety line of defense;

2) The self tightening stress of the seal without trapezoidal thread is better than that of the seal with trapezoidal thread, but the influence of medium pressure fluctuation is considered in the design of the compression load of the seal components of the two schemes, and the self tightening stress only provides auxiliary sealing load;

3) The bottom end of the pressure housing with trapezoidal thread seal structure is fixedly connected with the penetration by the trapezoidal thread, so that the pressure housing and the penetration become a whole, which will not cause frequent irregular extrusion to the graphite ring structure of the seal assembly and has little impact on the sealing performance;

4) The compression nuts of the two schemes are provided with the same jacking screws to realize the mechanical locking.

Because the nut compression load and self tightening stress meet the sealing requirements, and the pressure shell bottom and the penetration end thread are connected and fixed, the possibility of relative swing between the pressure shell and the penetration is greatly reduced, and the sealing performance is relatively more reliable. At the same time, considering the operation safety, the new sealing structure scheme with trapezoidal thread can be preferred.
5. Conclusion
The developed CRDM pressure hull seal structure, which is suitable for special marine environment and meets the requirements of multiple refuelling, is an important way and key technology to improve the refuelling efficiency, shorten the refuelling cycle and reduce the refuelling cost. In this paper, two new sealing structures (without trapezoidal thread connection and with trapezoidal thread connection) of the pressure shell of the control rod drive mechanism are proposed, and the new sealing structure design and performance analysis are carried out. It has the advantages of convenient and efficient installation and disassembly, simple operation, and easy replacement of sealing elements, so as to effectively reduce the radioactive medium in the refueling process. The irradiation effect creates conditions, which effectively avoids the harsh requirements of the traditional welding seal structure multiple cutting on the material and the quality inspection after welding, and lays the foundation for the practical application of engineering.

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