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Design Optimization and Fabrication Method Development Considering the Manufacturability of HCCP TBM Shields

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1. Introduction

A key aim of the ITER project is to conduct experimental research into heat extraction and tritium breeding using the Test Blanket Module (TBM) [1–8]. In this context, Korea and Europe, as ITER members, have independently developed various TBM concepts, such as the Helium-Cooled Ceramic Reflector (HCCR) blanket, the Helium-Cooled Pebble Bed (HCPB) and the Water-Cooled Lithium Lead (WCLL) TBMs. Recently, both countries agreed to collaborate on the joint development of a TBM. Under this agreement, the HCCP TBM is being co-designed by both parties [9]. The HCCP TBM combines HCCR and HCPB concepts, consisting of two main components: the TBM box and the TBM shield, as shown in Fig. 1. In this design stage, Korea is responsible for developing the TBM shield.

The HCCP TBM shield comprises a structure of five blocks with piping connections consisting of water and helium inlets and outlets, purge gas inlets and outlets, and NAS I&C piping, which run through these five blocks and connect to the TBM manifold. The existing Helium-Cooled Pebble Bed (HCPB) TBM shield design includes multiple reinforcement plates, which present challenges in terms of welding and inspection, as well as significant manufacturability issues. These features complicate welding and inspection, often requiring precision techniques that increase time and cost, as well as the potential for defects.

In this study, we propose a novel manufacturing approach for the HCCP TBM shield that simplifies its internal structure and reduces the number of reinforcement plates required. This approach aims to optimise the fabrication process, improve welding accessibility, and enhance joint inspectability using non-destructive testing methods. Thermal-hydraulic and mechanical analysis has validated the structural integrity of the simplified design, ensuring compliance with ITER safety and performance requirements. The results of this work are expected to significantly improve manufacturability.

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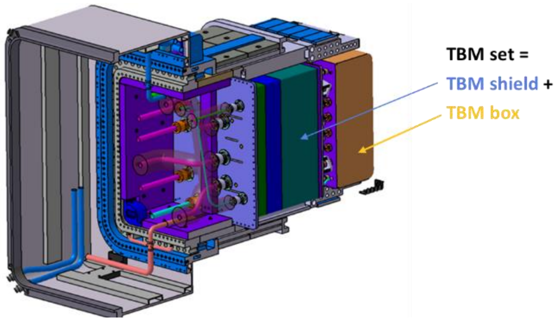

Fig. 1. HCCP TBM geometry diagram

2. HCCP TBM Shield Fabrication Processes and Methods

The fabrication process for the HCCP TBM shield begins with a detailed design analysis and simulation to evaluate its behaviour under operating conditions, such as thermal stress and mechanical load. The main fabrication process involves welding the main block and several reinforcing plates, giving the shield the characteristics of European TBM designs, such as HCPB and WCLL. The HCPB TBM shield structure consists of three blocks, 32 internal reinforcing plates and four transverse reinforcing plates. This complex geometry necessitates a complex welding process involving precision welding, which is labour-intensive and prone to errors. This paper presents a novel approach to optimising the design, simplifying the welding process and improving manufacturability. This includes reducing the number of reinforcement plates and improving the geometric design to facilitate assembly.

As illustrated in Fig. 2(a) and 2(b), the enhanced TBM shield boasts a streamlined design comprising five primary shield components. We have developed an assembly sequence for the improved HCCP TBM shield. In the previous HCPB TBM shield design, the spacing between the internal plates was relatively narrow. This imposed limitations on fabrication and weld inspection, particularly with regard to access for non-destructive testing (NDT). To mitigate these issues, the spacing between the internal plates was increased in the current design, thereby reducing the number of welds and improving accessibility for inspection. To maintain structural stiffness and counteract the reduced steel fraction caused by fewer internal plates, the thickness of the internal plates and external walls of the TBM shield was increased. This modification improves manufacturability while preserving mechanical integrity, as validated by structural analysis results.

3. Thermal-hydraulic and Thermo-mechanical Analyses of the TBM Shield

Thermal-hydraulic and thermo-mechanical analyses were performed on the improved HCCP TBM shield geometry. Under normal ITER operating conditions, water at 4 MPa and 70°C flows inside the TBM shield to cool it. A thermal-hydraulic analysis was performed to simulate this scenario. The TBM shield has an inlet and an outlet for cooling water at the rear end. The cooling water flows through channels formed inside the shield. According to the thermal-hydraulic design constraints, the cooling water pressure drop should be approximately 1.29 MPa and the maximum structural temperature should be kept below 475 °C to prevent excessive material creep. The thermal-hydraulic analysis was performed using the boundary conditions illustrated in Fig. 3. This analysis was carried out with a mass flow rate of 5.5 kg/s, an inlet temperature of 70 °C and an outlet boundary set to a relative pressure of 0 Pa.

The shield comprises multiple internal blocks separated by plates. Flow holes in these plates guide the coolant through sequential downstream and upstream paths, minimizing stagnant regions and promoting uniform thermal transport, as shown in Fig. 4. The analysis results showed a pressure drop of approximately 1.15 MPa, determined from the pressure difference between the inlet and outlet boundaries, and a maximum temperature lower than the limiting temperature inside the TBM shield structure, as shown in Fig. 5.

A thermo-mechanical analysis was performed using the boundary and support conditions shown in Fig. 5. Since the TBM shield is fixed to the TBM port frame, fixed constraints were set to reflect the geometry of the frame. In the current design, process pipes are not included in the thermo-mechanical analysis due to the pending confirmation of the pipe-to-flange connection scheme. However, the pipes include bending sections, and a double bellows-type flexible joint is being considered to allow for thermal axial expansion. To prevent contact with or stress concentration against the shield casing, sufficient clearance is maintained and the pipe is configured so that one end is unconstrained, enabling thermal displacement to be absorbed during operation. These design considerations are reflected in the structural layout and will be integrated into future analyses once finalised.

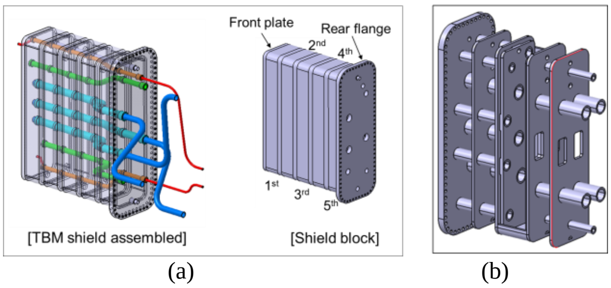

Fig. 2. Schematic of revised HCCP TBM shield: (a) HCCP TBM shield geometry; (b) Internal structure of the HCCP TBM shield geometry

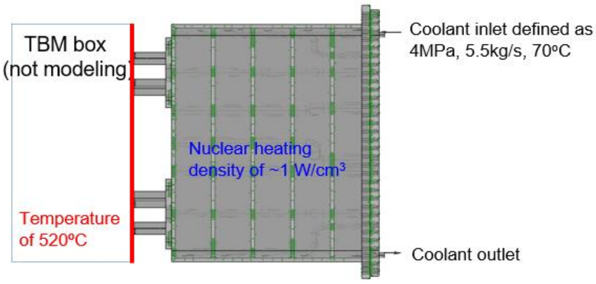

Fig. 3. Boundary condition for TH (Thermal-Hydraulic) analysis

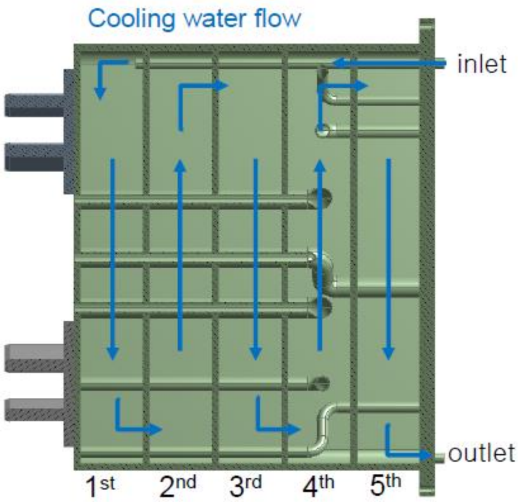

Fig. 4. Cooling water flow diagram

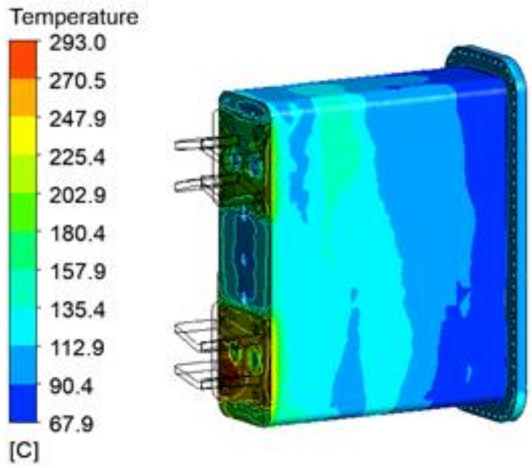

Fig. 5. Temperature distribution on HCCP TBM shield

4. Conclusions

Korea and Europe have agreed to collaborate on the design and manufacture of a new HCCP TBM, which will combine the advantages of the HCCR and HCPB TBMs for use in the ITER project. Conventional complex-shaped TBM shields have been difficult to manufacture due to the complex welding process required. This paper presents a TBM shield manufacturing method that optimises the design, simplifies the welding process and improves manufacturability. Additionally, the simplified structure is expected to facilitate the application of visual inspection methods for UT and NDT. A manufacturing procedure for the HCCP TBM shield is presented. Thermal-hydraulic and thermo-mechanical analyses were performed on the improved HCCP TBM shield shape, and the results confirmed that it satisfies the design requirements.

Acknowledgments

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