Design and R&D Progress of ITER HCCR TBM development for Fusion Breeding Blanket

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1. Introduction

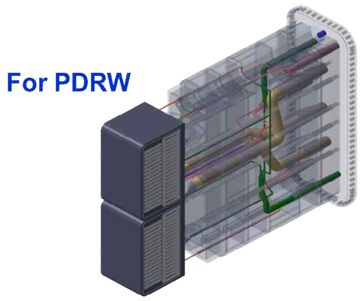
Korea has designed a helium cooled ceramic reflector (HCCR) test blanket module (TBM) including the TBM-shield, which is called the TBM-set, to be tested in ITER, a Nuclear Facility INB-174[1]. Under the TBM program, the National Fusion Research Institute (NFRI) is leading and the Korea Atomic Energy Research Institute (KAERI) is collaborated to design and to develop the key technologies with the collaboration of universities, industries.

Through the conceptual design review (CDR), its design integrity was successfully demonstrated at the conceptual design level at various loads [1-15]. After CD approval, preliminary design (PD) was started and the progress is introduced in the present study. After PD review and approval, final design and then fabrication will be started. The main purpose of PD is to design the TBM-set according to the fabrication aspect and more detailed design for interfaces with ITER machine, such as installed TBM port plug and frame. With these considering, PD of TBM-set was started. Figure 1 shows the main change of the design parameters for each TBM-set design phase; breeder material was changed Li4SiO4 to Li2TiO3 and it affects the temperature limit and enrichment of the Li-6; Graphite reflector was changed pebble type to block type and it affects the radial dimension of the TBM; as a results of the TBM-set design, the total weight was changed 5.552 tons to 5.124 tons and the limitation of RAFM steel (1.3 ton) was satisfied to be 1.163 tons.

Currently, the R&D activities for the development of HCCR TBS were performed in the areas of structural and breeder material development, the fabrication method of a submodule, graphite pebble fabrication, and coating technology for a tritium permeation barrier. The recent design and R&D progress of the HCCR TBS development in Korea are introduced in this paper.

2. TBM-set design progress

Several requirements were decided for the design of HCCR TBM. A 15 mm gap from the port frame to TBM and a 120 mm recession were considered. Since the port dimension was fixed, the TBM dimension was decided to be 1670 mm in height and 462 mm in width. Surface heat flux from the plasma side is 0.35 MW/m^2. Considering the design requirements of DEMO relevancy, the size compactness for delivery for PIE (Post Irradiation Examination), and adopting a graphite reflector as a unique feature of the concept, a vertical HCCR TBM concept was developed. It has four sub-modules with major components such as a First Wall (FW) that has 11 cooling channels with 15 mm in width and 11 mm in height, a Side Wall (SW) with a complicated cooling path, a Breeding Zone (BZ) with a seven-layer breeding zone in each sub-module, and a Back Manifold (BM) common to all sub-modules, as shown in Fig. 1. The four sub-module concept was used and accounted for manufacturing and easy PIE aspects. According to the operation window and coolant conditions of the structural and functional materials, the temperature limits were decided not to exceed about 550 °C and 920 °C, respectively.



Parameter	Values
FW heat flux	0.3 MW/m^2
Neutron wall load	0.78 MW/m^2
Thermal Power	0.98 MW
Structural material	KO-RAFM (ARAA) (< 550 °C)
Breeder	**Li_2TiO_3** pebble (< 920 °C)** **70%** enrichment Li-6
Multiplier	Be (< 650 °C)
Reflector	Graphite (**block type**, <1200 °C)
Size	1670(P) x 462(T) x **535**(R) (mm)
Weight (TBM/FMS/shield)	**5.126 tons** (1.363 / 1.163 / 3.763)
Coolant	8 MPa He 1.14 kg/s (Nominal) FW (300 °C/390 °C) Breeding Zone (390 °C/500 °C)
Purge gas	He with 0.1 % H_2

Fig. 1. Main design parameters of TBM-set at PD phase

From the basic design of the HCCR TBM and the above design requirements, a detailed design of each component was performed on (1) FW that considers cooling under a structural material temperature limit, (2) a BZ layer for obtaining tritium breeding ratio and cooling with breeder, reflector, and multiplier pebbles, (3) a SW that considers the flow distribution to BZ and internal pressure, (4) BM for a uniform flow to FW cooling channels, and (5) a He purge line in BZ that considers purge gas distribution. Based on the design analysis with the CFD code, ANSYS-CFX, with the results of nuclear heating by neutronic calculation, in which MCNP5 version 1.40 and FENDL 2.1 were used for neutron transport code and nuclear data library, respectively, it was confirmed that their performances satisfied the design requirements of HCCR TBM.

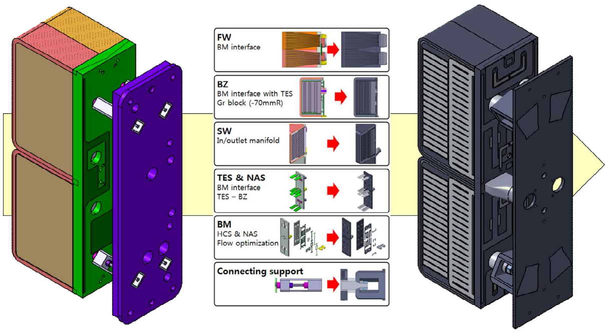


Fig. 2. Main design changes of the TBM-set in the PD phase

3. Development of the key technologies for TBM-set

3.1 Structural material development

Efforts have been made to develop an advanced structural material for the HCCR TBM application, called ARAA (Advanced Reduced Activation Alloy), with superior mechanical properties such as impact and creep resistance at high temperatures. An alloy design with two different strategies was made: One is modification of the amounts of alloying elements such as C, Cr, W, V, Ta, N and Ti, and the other is to examine the potential role of alloying elements, e.g., Zr, that have rarely been used in the conventional blanket structural steels. With these strategies, a total of 73 alloys were designed and fabricated, and the mechanical properties were evaluated. A process design was made to optimize heat treatment (i.e., normalizing and tempering) conditions for new alloys. Based on the out-of-pile performance test results, two ARAA alloys were selected, for which 5-ton, 6-ton, 18-ton scale heats were fabricated as plate type with various thicknesses by Korean industries, as shown in Fig. 3. The plates were used to optimize the processing variables that vary depending on the size of products and to evaluate the mechanical properties in order to assess reproducibility. A part of the tempered plates were utilized for irradiation and PIE and an in-pile test of the commercial scale ARAA using High-Flux Advanced Neutron Application Reactor (HANARO) is being performed. Based on the results of the irradiation tests, the final candidate will be chosen and produced on a large scale, which in turn will be utilized for the fabrication of the HCCR TBM.

Fig. 3. ARAA-3 18 ton fabrication

3.2 Functional materials development

Two types of Li2TiO3 (LT) and Li4SiO4 (LS) breeder pebbles were developed, but LT was finally selected as a breeder considering its superior properties and integrity. It is fabricated by slurry droplet wetting method based on the cross-linking reaction between polyvinyl alcohol (PVA) and boric acid, and by using the decomposition reaction of hydrogen peroxide (H2O2) solution, respectively. The average diameter and grain size of sintered pebbles were about 1 mm and 10 μm, respectively. The whole pore of the sintered Li2TiO3 pebbles were open type and the open porosity was about 10%. In addition, an automatic dispensing system of the high viscosity ceramic slurry is being developed for mass production of the ceramic breeder pebbles. Also, the development of a powder synthesis process for the high purity and fine grains is ongoing.

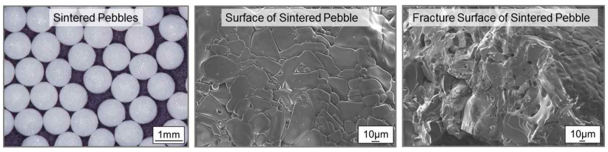


Fig. 4. LT mass production and its microstructure

3.3 Fabrication technology development

The fabrication procedure of a sub-module first fabricates each part of FW, BZ, and SW, and then assembles the fabricated parts using welding. A fabrication process of the FW was developed and a half-scale sub-module FW was fabricated and tested. The fabrication sequence of the BZ and SW machines each part and then welds the parts using TIG welding and E-beam welding. The sub-module is finally assembled with the FW and BZ-SW parts using E-beam welding. A real scale sub-module mock-up will be fabricated with ARAA steel to verify the welding performance and the fabrication process.

At first, the fabrication procedure were developed, as shown in Fig 5. To verify the welding performance of the ARAA steel for TIG welding and E-beam welding, a series of tensile, face bending, root bending and V-notch impact tests will be carried out. The test specimens were designed and are being fabricated now. A small BZ mock-up was designed to verify the welding process and welding performance. The BZ mock-up is being fabricated with ARAA steel to verify the welding performance and the fabrication process of the breeding box. The height of the mock-up is 240 mm, and its width and length are 191 mm and 240 mm, respectively.

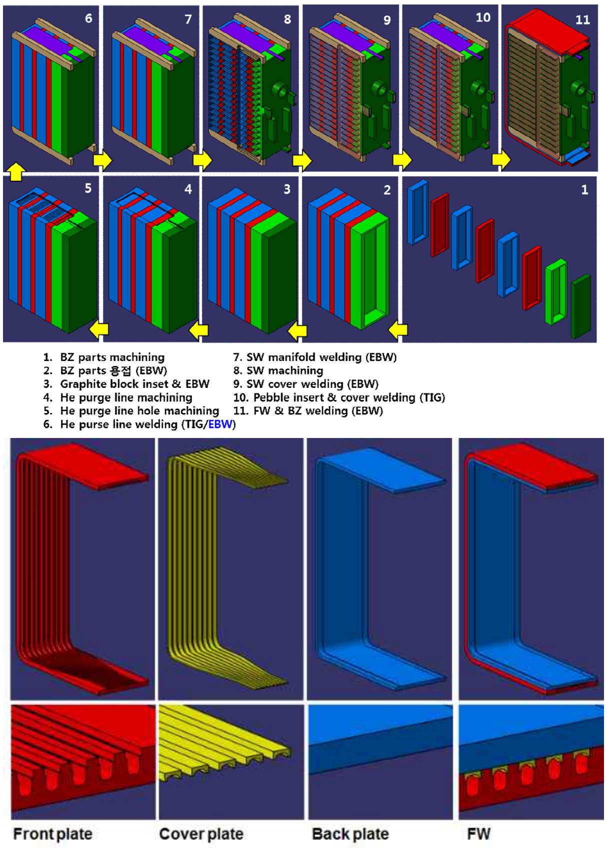


Fig. 5. Fabrication procedure of the TBM-body

3.4 He cooling technology development

The Helium Supply System (HeSS) was upgraded by adopting a diffusion-bonded heat exchanger (so-called PCHE, printed-circuit heat exchanger) type recuperator and cooler in order to dramatically reduce the required electrical power of the helium pre-heater down to 150 kW and to improve the operational stability, as shown in Fig. 6.

The PCHE type recuperator was selected because of its high efficiency and compactness. The HeSS can supply a high pressure of 8 MPa and a high temperature of 300-500 ^{o}C helium gas with a mass flow rate of 0.5 kg/s. The helium mass flow rate is controlled by handling the rpm of the circulator and/or handling a bypass flow, and the temperature is controlled by the electric power of the pre-heater and/or handling the other side bypass flow. The HeSS is linked to an electric beam facility [17] that supplies a high heat flux of up to 0.5 MW/m2 to validate the design and manufacturing techniques for the first wall of the HCCR TBM and to obtain thermal-hydraulic experimental data for the verification and validation of the GAMMA-FR code.


Fig. 6. He supply system

3.5 Tritium technology development

It is essential to check tritium mass balance in the TBS to fulfill the objectives of the TBM program. Parasitic effects, like tritium permeation, should be properly evaluated or minimized to reduce the uncertainties. The HYPER (Hydrogen PERmeation) facility was established to investigate hydrogen permeability, diffusivity and solubility on fusion structural materials, and to evaluate permeation barrier coating technology. Currently, permeation tests are being carried out using SS-316L for the purpose of comparison with existing data. Eventually, various experiments using ARAA were performed with this facility.

Fig. 7. PG loop

Coating technology was developed for a tritium permeation barrier layer. Ceramics with high density can be good materials for the barriers because of the low solubility of tritium into ceramics. Aluminum oxide was formed successfully using a physical vapor deposition. The alumina coated samples are expected to evaluate their resistances to tritium permeation using a HYPER. Sol-gel based coating was developed to form a coating layer on the inside of tubes. The density of the coated layer was very low. The phase of the formed oxide was amorphous for the most part. Accordingly, more attention needs to be paid to develop the coating technology to recover these problems.

3.6 Liquid breeder technology development

In order to develop the liquid breeder technology, the analysis methods of its behavior under an electro-magnetic field (MHD, magneto-hydrodynamics), compatibility with structural materials, and key-components such as electro-magnetic pump are essential. An experimental loop with PbLi, shown in Figure 4, was established at KAERI for performing the above essential experiments. The design parameters are as follows: over 250 ºC of temperature, 0.5 MPa of pressure, up to 60 lpm of flow rate, and 2 T of magnetic field in the magnet.

Fig. 8. PbLi loop in KAERI

4. Conclusions and future works

PD for HCCR TBM has been performed (so far v0.24) from the CD model. FW, BZ, SW, TES/NAS, BM, and connecting support design were performed through the analyses, if necessary. The manufacturability was the main concern for PD model development. As well as the design, key technologies such as structural and functional materials, fabrication method, high temperature and high pressure He cooling technologies, and tritium related R&Ds.

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