CURRENT DESIGN AND R&D PROGRESS OF CN HCCB TBS

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Abstract

As the testing mockup of tritium breeding blanket for DEMO, Chinese Helium Cooled Ceramic Breeder Test Blanket System (HCCB TBS) is under developing by China and will be tested in ITER to verify the key tritium breeding blanket technologies. After the approval of conceptual design of HCCB TBS by ITER Organization in 2015, the design optimization and more R&D activities for HCCB TBS have been started for preliminary design. The paper gives an overview of the recent progress of the HCCB TBS development in China, including design optimizations, material development, mockup fabrication and test facility construction.

1. INTRODUCTION

In order to verify the key technology of tritium breeding blanket toward DEMO, China will design and fabricate Chinese Helium Cooled Ceramic Breeder Test Blanket System (CN HCCB TBS) that will be tested in ITER to obtain the performance data related to tritium behaviours, heat removal capability and so on [1] [2], which will give support for the design of helium cooled ceramic breeder tritium breeding blanket of China Fusion Engineering Test Reactor (CFETR) and future DEMO [3].

Since the approval of conceptual design by ITER Organization in 2015, the design optimization and R&D have been implemented mainly considering the system performance, manufacturability, safety and interface based on the requirements of preliminary design phase. Under the supporting by the current design and R&D activities, it is expected to complete the preliminary design in 2020.

2. SYSTEM OVERVIEW

According to the testing objectives of HCCB TBS, HCCB TBS comprises several subsystems to achieve the testing functions, including test blanket module set (TBM-set), helium cooling system (HCS), tritium extraction system (TES), coolant purification system (CPS), tritium accountancy system (TAS) and neutron activation system (NAS). All these subsystems are located in the different rooms in ITER buildings and connected by the connection pipes (CP). Besides, some equipment of subsystems located in port cell form ancillary equipment unit (AEU) together with the structure frame. The pipes connecting TBM-set and AEU form pipe forest (PF) together with the structure frame. The AEU and PF are shared with other TBS in the same port [4]. The global layout of the HCCB TBS in ITER building is shown in FIG.1.

The TBM-set consists the Test blanket module (TBM) and the TBM shield, which is located in the TBM frame installed in the port of ITER vacuum vessel. The TBM is the core component of the HCCB TBS that directly faces plasma and produces the tritium under fusion neutron irradiation. The TBM shield is just behind TBM to provide the neutron shielding. The HCS uses 8 MPa helium gas as coolant to remove the thermal power generated in TBM and release to the ITER Components Cooling Water System-1 (for nuclear components). The CPS provides functions of coolant composition control and tritium purification from coolant. The TES extracts the
tritium generated in TBM by the 0.3 MPa helium purge gas blowing the tritium breeding zone inside TBM and the TAS monitors the tritium in the TES. The neutron spectrum at the specified location in TBM is measured by the NAS.

3. DESIGN OPTIMIZATION

As the core component of the HCCB TBS, the TBM has the function of tritium breeding and structure integrity under ITER fusion operation condition. It consists of tritium breeding zone filled by lithium silicate pebble, neutron multiplying zone filled by beryllium pebble and box structure with cooling channels made by the reduced activation ferritic/martensitic (RAFM) Steel CLF-1. [5]

After the conceptual design review, the TBM was significantly simplified considering the material performance, manufacturability, inspectability and ALARA principle, as shown in FIG.2. Mainly the back plate was simplified from seven layers to three layers and its chambers for coolant distribution were optimized, which allows its fabrication by machining and few welding. Considering the segregation effect of binary pebble bed, the binary beryllium pebble bed was changed to unitary pebble bed in order to keep the uniform distribution, especially after vibration. The thickness of multiplier zone in the TBM was reduced considering the thermal conductive performance of unitary pebble bed, at the same time the enrichment of lithium 6 was increased in lithium silicate. These design optimizations impact the whole integration method of TBM and the fabrication procedure plan has been updated. Besides, the operation pressure of the TES increased from 0.1 MPa to 0.3 MPa and the flow mass increased from 0.1g/s to 0.3g/s considering the pressure drop and tritium concentration respectively, which do not impact the design of TBM. As the result, the weight of RAFM steel is reduced from 1.32 ton to 1.2 ton, which is helpful to reduce the ripple of Tokamak magnetic field and future radwaste.

During the design optimization, all related analysis were performed to verify the reasonability. The results show that the total heat deposition in the TBM was similar with conceptual design, while the tritium production ratio (TPR) was slightly higher. The helium coolant and purge gas in the TBM were uniformly distributed, with maximum deviation of 6.2% and 2.7% respectively. The maximum temperature and stress of different materials were all below the limits. After design optimization, the main design parameters of the TBM is given in TABLE 1. And the thermal structural analysis results are shown in FIG.3 and TABLE 2. [6]
FIG. 2. Design optimization of TBM

TABLE 1. MAIN PARAMETERS OF TBM AFTER DESIGN OPTIMIZATION

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron wall load</td>
<td>0.78 MW/m²</td>
</tr>
<tr>
<td>Surface heat flux</td>
<td>0.3 MW/m²</td>
</tr>
<tr>
<td>Structural material</td>
<td>RAFM steel (CLAM or CLF-1) (&lt;550°C) ~1.2 ton</td>
</tr>
<tr>
<td></td>
<td>LiSiO₄ pebble (&lt;900°C)</td>
</tr>
<tr>
<td>Tritium Breeder</td>
<td>Packing factor: 62% (unitary)</td>
</tr>
<tr>
<td>Neutron Multiplier</td>
<td>Beryllium pebble (&lt;650°C)</td>
</tr>
<tr>
<td></td>
<td>Packing factor: 62% (unitary)</td>
</tr>
<tr>
<td>Coolant</td>
<td>Helium (8MPa) (300°C/500°C) ~1.04 kg/s</td>
</tr>
<tr>
<td>Purge gas</td>
<td>Helium (0.3MPa) with 0.1% H₂</td>
</tr>
<tr>
<td>TPR</td>
<td>0.061 g/FPD</td>
</tr>
</tbody>
</table>

FIG. 3. Stress distribution of TBM submodule under normal operation load condition
TABLE 2. LINEARIZED STRESS AND ALLOWABLE CRITERIA

<table>
<thead>
<tr>
<th></th>
<th>Pm Allowable</th>
<th>Pm+Pb Allowable</th>
<th>Pm+Pb+△Q Allowable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrostatic test</td>
<td>&lt;162MPa</td>
<td>291.6MPa @20ºC</td>
<td>735.75MPa @20ºC</td>
</tr>
<tr>
<td>Normal operation</td>
<td>&lt;84MPa @500ºC</td>
<td>148MPa @500ºC</td>
<td>222MPa @500ºC</td>
</tr>
<tr>
<td>In-box LOCA</td>
<td>&lt;174.7MPa</td>
<td>200MPa @500ºC</td>
<td>300MPa @500ºC</td>
</tr>
</tbody>
</table>

The design of TBM shield was also optimized, with only a few welding joints existing at the shell as external vacuum boundary and the internal plates can be partially welded or bolted with shell. In order to mitigate the thermal stress of high temperature pipes, three pipes in TBM shield were changed from 2 bends to 4 bends and the thickness of back plate was reduced from 90mm to 60mm, which significantly reduce the weight of TBM shield [7].

After conceptual design review, the design of all ancillary systems have been optimized considering the review comments, safety and interface requirements, especially the layout configuration of HCS has been updated based on the constraints of power supply, which result in adding one transformer in HCS. Accordingly the Process Flow Diagram (PFD) and Pipe & Instrumentation Diagram (PID) have been updated [8], but still some interface issues with ITER have been identified and have to be solved. The system performance has been assessed considering plasma pulse operation and operation status shift in order to optimize the operation control plan and equipment requirements. Following EN13480 and EN13445, the structural analysis have been performed to verify the new design configuration. The results show that the stress of pipeline and reaction force of embedded plates meet the standard and ITER requirements.

4. R&D PROGRESS

4.1. Material development

As the candidate structural material of the TBM, the Chinese low-activation ferritic/martensitic steel (CLF-1), one kind of RAFM steel, has been studied and developed by Southwestern Institute of Physics (SWIP) since 2003 [9] [10], and its industrialized fabrication process based on 5 tons scale ingot was finalized in 2016 [11]. Recently eight tons plates and forgings of the CLF-1 steel (FIG.4), from three five-ton ingots, have been fabricated based on the industrialized manufacture technique with the chemical composition Fe-8.58~8.61Cr-1.41~1.47W-0.24~0.32V-0.49~0.61Mn-0.08~0.1Ta-0.085~0.092C-0.015~0.04N (wt.%) [12]. Nb, Mo and Co have been controlled under 0.01 and 0.005% considering their radiological activation in ITER. A certification of 3.2 requested by EU Pressure Equipment Directive 97/23/EC (PED) has been obtained for the CLF-1 steel under the witness of Notified Body (NB) based on the CLF-1 steel technical specification. These materials have been used in the R&D activates for TBM fabrication processes. Considering the operation condition of TBM, a preliminary study of corrosion behaviour of CLF-1 in TBM helium coolant had been performed under the environment of helium (99.9%) and hydrogen (0.1%) with total impurity elements including O₂, CO₂, H₂O less than 10ppm at 500ºC and 8MPa pressure for 100 hours. The experiment results indicated that no interaction between helium and CLF-1 steel observed except for the oxidation. Further study with strictly control oxygen content of the whole experimental system has been planned.
The fabrication technique, rotation electrode process, has been developed for the production of neutron multiplier beryllium pebble together with industry and the properties have also been tested [13] [14]. Recently the fabrication facility for beryllium pebble has been updated in order to improve the product output. After updating, the production scale has achieved ~10kg/batch and 5 more kg beryllium pebble has been fabricated with the properties Be>98.5%, BeO<1.0%, pelletizing ratio >60% and pebble diameter in the controllable range of 0.5-1.5mm. The He+ implantation experiments were performed for beryllium samples to investigate the effect of helium on the micro-structure and hardness of beryllium material. The results show that the probability of beryllium pebble crushing increase with the increase of irradiation FIG.5.

The melt spraying process is used to fabricate tritium breeder lithium silicate pebble and several batches have been fabricated and tested by this process [15]. A new manufacture facility for lithium silicate pebble is under construction and its production rate will satisfy the requirements of TBM.

In order to assess the packing of pebble bed for beryllium pebble and lithium silicate pebble, the packing structures of pebble bed with unitary-sized pebble and binary-sized pebble for actual space in TBM and the compression behavior have been assessed by both discrete element method (DEM) and experiments [16]. Both simulation and experiment results show that the packing factor of unitary-sized pebble beds can achieve 0.62-0.64. However, the uniformity of binary-sized pebble bed is poor, which may lead to segregation of binary pebble and the non-uniform distribution of temperature, stress and purge gas in pebble bed. Based on this result, it has been decided that only unitary-sized pebble will be used in TBM to avoid the possible segregation of pebble bed.

4.2. TBM fabrication technology

As a very complicated box structure, the fabrication technology of TBM is one of the most important challenges to achieve the requirement of pressure equipment. In the past several years, several potential welding methods have been investigated, such as tungsten inert gas welding (TIG), laser beam welding (LB), electron beam welding (EB), hot isotactic pressing welding (HIP) and vacuum hot pressing welding (VHP). Based on the
investigation and RCC-MR requirements, it is considered to use the LB welding and EB welding as the main welding methods for the fabrication of TBM, and TIG welding as the supplementary method.

For the LB welding, CLF-1 steel welding technology of thickness from 5mm to 35mm had been developed. The thickness by single pass LB welding could achieve maximum 17.5mm. After the post weld heat treatment (PWHT), the tensile strength at the welding joint was larger than the base material and the impact energy achieved 200J [17]. 35mm thickness LB welding of CLF-1 was achieved by narrow-gap laser welding process using Ø1.2mm CLF-1 wire filler material. After the PWHT, the ultimate tensile strength of the welding joint was 626 MPa@RT and 357MPa@550℃, but the impact energy fluctuated in the range from 22J to 306J, which is under study now by more experiments [18]. For the EB welding, the welding technology of CLF-1 based on 32mm and 50mm thickness has been studied. The microstructure has been observed, hardness and tensile strength have been tested after the PWHT process [19]. Besides, the dissimilar welding of CLF-1/316L steel by TIG welding was studied. Due to the different properties of the two materials, the ER316 was used as transitional layer and filler material. After the PWHT, the tensile strength of the welding joints was no less than the base material. The impact energy was usually higher than 41J but lower than the base material.

Based on the above research on the welding technologies, the suitable welding methods have been selected and utilized for the fabrication of the component samples to verify their application feasibility for the TBM. Following the fabrication procedure plan of TBM, the full size mockups of key components, including first wall, cooling plate, back plate, breeding unit, double-layer pipe, etc., have been fabricated and tested, such as dimension, pressure test and helium leakage test, as shown in FIG.6. Using these mockups, the semi-prototype of TBM is under fabrication to verify the final integration process.

FIG.6. TBM fabrication technology development

4.3. Helium cooling technology

In order to verify the helium cooling technology and its control, one small helium cooling experiment loop (HeCEL-1) has been constructed and tested by SWIP. The operation pressure and helium flow rate are 8 MPa and 0.1kg/s, respectively. The temperature at experimental section can achieve 400℃ [20]. After commissioning of
the HeCEL-1, ITER Mini-CODAC was connected and realized the control function under ITER control framework. HeCEL-1 is also connected with 60kW high heat flux testing (HHFT) facility (EMS-60), as shown in FIG.7, which is the first high temperature and high pressure helium experiment loop with high heat flux test capability for fusion research in China. Based on this, the hydraulic test of breeding unit and the high heat flux test of FW sample were carried out.

Currently, a new circulator with 0.5kg/s helium flow rate is under development and will be tested in the HeCEL-1. If it is successful, the HeCEL-1 will be updated to 0.5 kg/s flow rate, which will be helpful for the future thermohydraulic test of TBM components.

5. SAFETY

Considering the nuclear safety and licensing aspects, further work have been performed with the collaboration with IO TBM team and safety team, including nuclear analysis to identify radioactive inventories and distributions, dose rate evaluation to demonstrate the radiation levels, multiple confinement barriers design to confine tritium and mobile radioactive dusts, tritium transport analysis to assess tritium release and contamination level assessment to check the compliance with ITER requirements. ALARA principle is kept in mind during the whole design phases, including selection of advanced materials, improvement of shielding, optimization of operation and maintenance activities, etc., to minimize the radioactive release and radioactive exposures. Several potential envelop accidents have been identified and analyzed, including loss of flow of cooling system, loss of coolant in different locations, break of tritium systems, break of heat exchanger between HCS and ITER water cooling systems, etc. During all accidents, because of the intrinsic safety characteristics of fusion device, after fusion plasma shutdown passively or actively, HCCB TBS has not over-temperature issues [21] [22] [23]. Considering the limited inventories and multiple confinement barriers, no major safety consequences had been identified through accident assessments.

6. SUMMARY

CN HCCB TBS is one of the most important part of China fusion development strategy toward DEMO. After the conceptual design approval in 2015, the design of the HCCB TBS has been significantly optimized and developed in detail according to the schedule, especially for TBM-set and HCS. In order to support the design optimization, a lot of R&D activities have been implemented, including structure material and function materials development, fabrication of TBM mock-up, construction of the testing loops and so on, but still many challenges remain and need to be solved during the design phase.
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REFERENCES


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