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Design and R&D Progress of Chinese HCCB TBM

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Abstract. China had promised to test its TBM modules during different ITER operation phase and have signed the CN HCCB TBMA with ITER IO recently. Related design and R&D activities for each TBM module with auxiliary systems and interface with ITER facility were introduced. The preliminary conceptual design of CN HCCB TBM has been completed while the design optimization is in progress. Basic characteristics and main design parameters as well as technical characteristics of CN HCCB TBM are introduced briefly. The neutron multiplier Be pebbles of kg-scale are fabricated by the Rotating Electrode Processing (REP). Be alloy are prepared by powder metallurgical (PM) methods. Be pebbles of diameters 0.5 mm and 1.0 mm as the neutron multiplier was fabricated. Related performance test is ongoing. The fabrication of pebble bed container and performance experiment of breeder pebble bed has being started. The lithium orthosilicate, Li_4SiO_4 pebbles with lithium 80% enriched in ^6Li as tritium breeding materials of HCCB TBM have been fabricated at laboratory level by melt-spraying method. Chinese Low-activated Ferritic/martensitic steel, CLF-1, as TBM structural materials is developing from laboratory scale towards industrial level. The structure material CLF-1 of ton-scale was recently produced by vacuum induction melting and electro-slag re-melting method. The mock-up fabrication and component tests by using the CLF-1 steel for Chinese test blanket module have being developed. Recent status on the fabrication technology development of CN HCCB TBM module was also reported.

1. Introduction

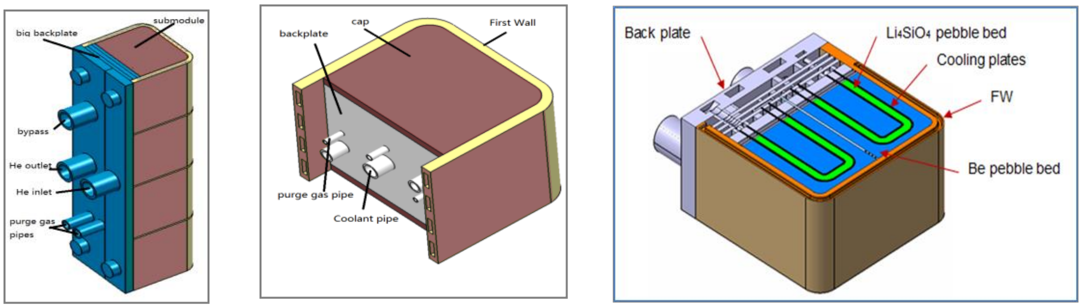
ITER will be used to test tritium breeding module concepts, which will lead to the design of DEMO fusion reactor demonstrating tritium self-sufficiency and the extraction of high grade heat for electricity production. China had promised to test its TBM modules during the ITER different operation phases. Related design and R&D activities for each TBM module with auxiliary system and interface with ITER facility were introduced.

The helium-cooled ceramic breeder (HCCB) test blanket module (TBM) is the primary option of the Chinese TBM program. The preliminary conceptual design of China helium cooled ceramic breeder test blanket module (*CN HCCB TBM*) has been completed. The CN HCCB TBM design optimization is under progress. Basic characteristics, main design parameters and technical characteristics of the CN HCCB TBM are introduced briefly.

2. Updated design of the HCCB TBS

2.1. Design of TBM Module

In the current conceptual design of TBM module with 1×4 configuration, as shown in Fig.1, there are 4 independent and identical sub-modules along the poloidal direction, and each sub-module has the corresponding Box assembly, which is consisted of the different structural parts of U-shaped first wall (FW), top/bottom cap, middle rib and rear manifold, just except the inner breeding zone of sub-module that includes the functional materials of Li_4SiO_4 and Be pebble beds and the relevant structural parts of 2 U-shaped cooling rings that are consisted of 2 pairs of cooling plates and 4 baffles. The coolant and purge gas pipes, shear keys, flexible supports and electrical connection are connected with TBM shield.



(a) TBM-set(module) *(b) Sub-module* *(c) Cross-section of sub-module*

Fig.1. Updated design of CN HCCB TBM module

TABLE 1. MAIN DESIGN PARAMETERS of CN HCCB TBS

Neutron wall loading	$0.78MW/m^2$
Surface heat flux	$0.3MW/m^2$
Total heat deposition	0.75MW
Tritium breeder	Li4SiO4 pebble 80% 6Li enrichment 62% packing factor
Neutron multiplier	Be pebble 80% packing factor
Structural material	RAFM steel (CLF-1)
Coolant Temp. (inlet) /(outlet)	He gas, 8.0MPa, $300^oC/500^oC$
Tritium purge gas	He gas, (0.1MPa)
Total weight: Structural material Functional material	 ~1.32 tons ~0.20 ton

In order to multiply neutrons and breed tritium, the breeding zone is located in the middle of the FW, cap and manifold. The Li_4SiO_4 and Be pebble beds are separated by the U-shape cooling rings and baffles [Ref. Fig.2]. In order to distribute and collect the coolant for the different structural parts in the sub-module, tritium purge gas for the Li_4SiO_4 and Be pebble beds, the manifold is located at the back of the sub-module.

As shown in Fig.2-3, the overall dimensions of HCCB TBM-set should refer to TBM frame design [1]. The dead weight of HCCB TBM-set should be below 7.5 tons, according to remote handling control requirements [2]. The diameters and positions of each pipe at the back of HCCB TBM-set should refer to port cell piping design and integration design [3, 4, 5].

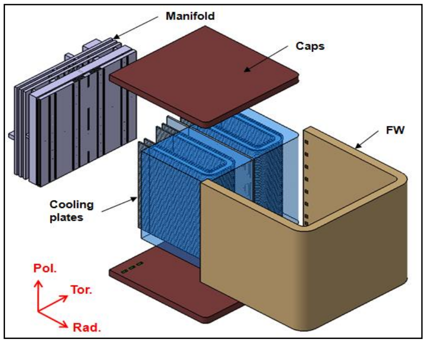


Fig.2. Component view of HCCB TBM Sub-module

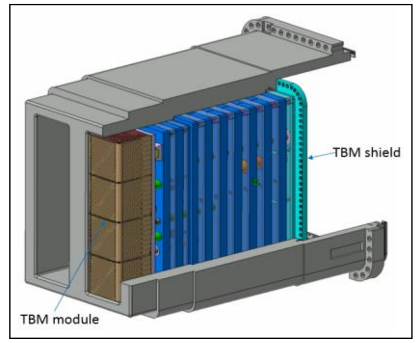


Fig.3. Schematic diagram of HCCB TBM-set

2.2. Performance analyses

The TBM box assembly is a pressure component that is very important for the sub-module under both the normal operation and the in-box loss-of-coolant (LOCA) accidental condition. Firstly, it is need to perform finite element (FE) stress analysis against P-type damage for the TBM Box of sub-module under normal operation.

The geometry model of the Box assembly is shown in Fig.3, which has the same outer dimensions of 430mm (radial) × 462mm (toroidal) × 410 mm (poloidal) with that of sub-module. The different constituent structural parts of the Box assembly are shown in the figure 2. The manifold is the most complicated part which is a multi plate-cavity structure, the cavity 1 to cavity 4 is used for distributing and collecting the coolant, the cavity 5 and cavity 6 is used for purge gas as shown in Fig.4.

The equivalent stress analysis results for the Box assembly are shown in Fig.5. It can be seen that the global equivalent stress is not high, and the maximum total stress of 261 MPa locates in the root position of stiffening plate of coolant cavity 2, where is also the area of stress concentration. Another high total stress of 231 MPa occurs in the that of coolant cavity 3, as shown in Fig.6, which both are greater than the 1.5 Sm at 500 ℃ (222 MPa), therefore, it is necessary to perform the linearized stress analysis. It is observed that the linearized stress results of both cavity 2 and cavity 3 meet the material allowable stress requirements at 500 ℃ based on the criteria RCC-MR 2007 of France nuclear pressure vessel design. Total deformation distribution of the Box assembly is shown in Fig.7, the maximum deformation is about 3.19×10^{-2} mm that occurs in the outer side wall of FW. The Fig.5 shows the flow velocity profile for Cavity in the Box manifold.

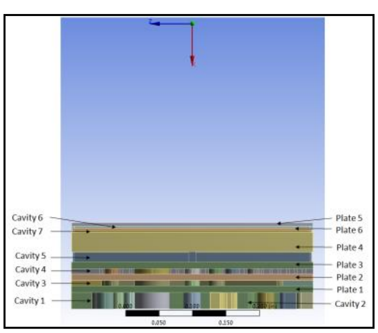


Fig.4 Structural analysis model for the Box manifold

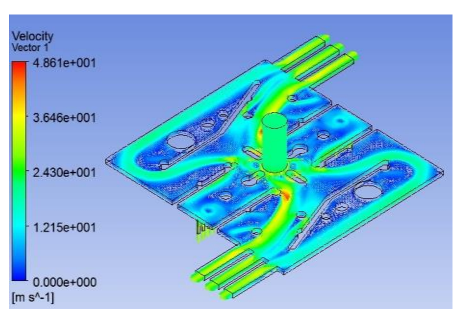


Fig.5 Flow velocity profile in Cavity 3

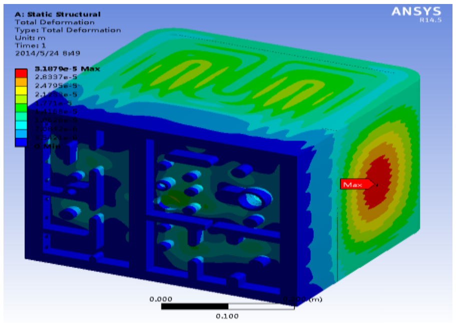


Fig.6 Global equivalent stress distribution of the Box

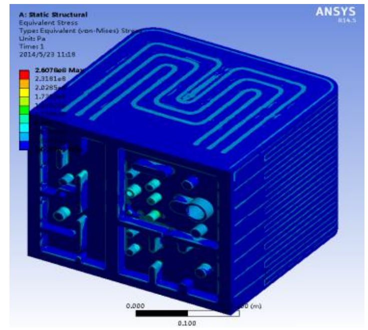


Fig.7 Global deformation distribution of the Box

The big back plate of TBM distributes coolant helium with the flow rate 1.04kg/s from inlet into first wall pipes and then part of it goes out by bypass and the rest 0.59kg/s goes into each sub-module and is distributed by manifolds in its back-plate to cool the middle plate and caps and then cool two double-layer U-shaped structures.

A simplified 1/2 dimensional symmetrical analysis model by taking advantage of the poloidal plane of symmetry is chosen for preliminary thermal-hydraulic analysis. With surface heat flux of 0.35 MW/m^2 from plasma and nuclear heat generation in different zones are shown in Fig.8. The mass flow rates between 5.50×10^{-4} and 8.37×10^{-4} kg/s are specified on inlets at temperature 416 ℃, which is based on flowing analysis results for coolant distributing cavity in the back-plate of the sub-module. In addition, approximate convective heat transfer coefficient was calculated by using the experimental correlations B.S. Petukhov equation [3], which is applied on the thermal-hydraulics for the channel surfaces of the FW, cap and rib. Calculation result for temperature distribution of the sub-module is shown in Fig.9. The maximum temperature of RAFMs, Be and Li_4SiO_4 pebble beds are 542 ℃, 509 ℃ and 760 ℃ respectively, which are below the allowable temperature limits (550 ℃, 650 ℃ and 920 ℃) [4].

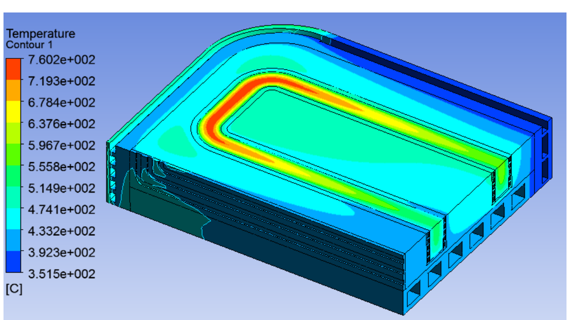


Fig.8. Temperature distribution of the sub-module

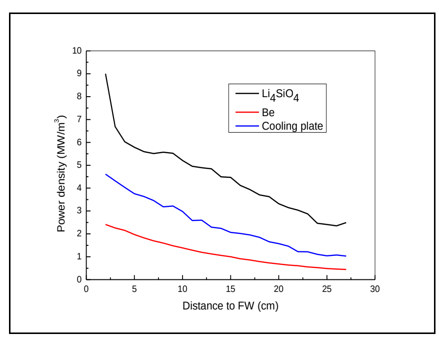


Fig.9. Power density distributions

Fluid analysis results show that mass flow rate of the coolant into the first wall pipes is in the range of 6.25×10^{-2}- 6.8×10^{-2}kg/s, that flowing into the branch channels of the middle plate is between 1.74×10^{-3} and 1.91×10^{-3} kg/s, and that in the channels of caps is between 2.18×10^{-2} and 2.38×10^{-2} kg/s. The mass flow rate in the channels of double-layer's U-shaped structures is between 3.52×10^{-4} and 1.05×10^{-3} kg/s.

2.3. Design of Ancillary System

CN HCCB TBS can be divided into several sub-systems configuration, which includes several subsystems as shown in Fig.10. The allocation layout configuration in the ITER building is given in Fig.11. For each sub-system on ITER test port are descripted, which are included:1）TBM set, 2）Helium cooling system (HCS), 3）Tritium Extraction System (TES), 4）Coolant Purification System (CPS), 5）Instrumentation and Control system (I&C), 6）Pipe forest (PF), 7）Ancillary Equipment Unit (AEU), 8）Connection Pipes (CP).

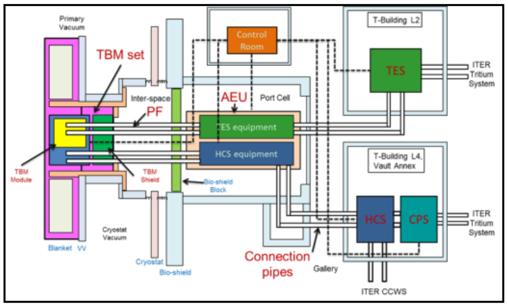


Fig.10 HCCB TBS system layout scheme

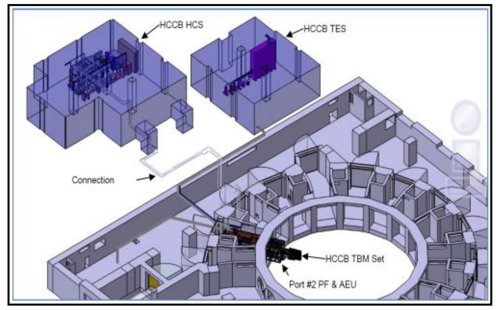


Fig.11 HCCB TBS allocation configuration

According to the load specification, the structural analyses have been performed based on each sub-system. The HCCB Test Blanket System (TBS) has reached conceptual design status. Design and analysis of the TBS have been completed for the conceptual design (CD) phase. The Conceptual Design Review (CDR) of the HCCB TBS has been completed in July of 2014.

3. Related R&D activities

3.1 Structure material-CLF-1

Chinese Low-activated Ferritic/martensitic steel, CLF-1, as TBM structural material, is developing from laboratory scale towards industrial level. The structure material CLF-1 of ton-class was recently produced in laboratory scale by vacuum induction melting and electro-slag re-melting method. The ingot was hot forged and hot rolled into different plates and rods. Some mechanical properties such as tensile and impact properties have also been tested. Some of properties test of the CLF-1 steel have been done. The creep and fatigue properties of the CLF-1 steel are shown in Fig.12-13.

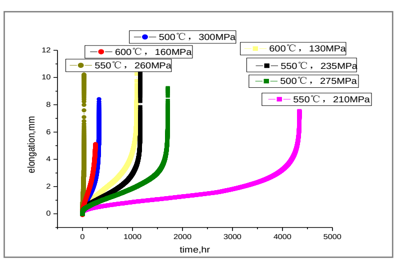


Fig.12. Creep properties of CLF-1 steel

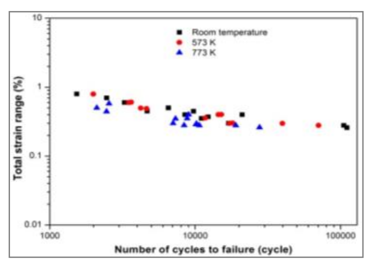


Fig.13. Fatigue properties of CLF-1 steel

The mock-up fabrication and component tests by using the CLF-1 steel for Chinese test blanket module have being developed. Recent status on the fabrication technology development of CN HCCB TBM module was also reported. A small-sized (1:3) mock-up of HCCB TBM components is proceeding as the large scale mock-up fabrication enters into the R&D stage and demonstration tests toward HCCB TBM testing on ITER test port are being done as scheduled. The components fabrication for TBM sub-module by the laser welding, EB, TIG and the vacuum thermal diffusion welding are shown in Fig.14.

(a) partition plate *(b) cooling plate* *(c) sub-module segment*

Fig.14. Mock-up for HCCB TBM sub-module's components

3.2 Tritium breeder- Li_4SiO_4

The lithium orthosilicate, Li_4SiO_4 pebbles with lithium 80% enriched in ^6Li as tritium breeding materials of HCCB TBM have been fabricated at laboratory level by melt-spraying method. Preliminary test results show that Li_4SiO_4 pebbles prepared by melt-spraying method have good mechanical intensity. Other one kinds of the solid tritium breeder, Li_2TiO_3 have also been investigated as alternative material of lithium orthosilicate, Li_4SiO_4. The Fig.15 shows the performance testing of Li_4SiO_4 pebble beds.

(a)Thermal diffusivity *(b) Thermal conductivity*

Fig.15. Performance testing of Li_4SiO_4 pebble beds.

3.3 Neutron multiplier

The neutron multiplier Be pebbles of kg-class scaled are fabricated by using the Rotating Electrode Processing (REP). The electrode of Be alloy using in REP process are prepared by powder metallurgical (PM) methods. Be pebbles of diameters 0.5 mm and 1.0 mm are fabricated. In the design, the filling ratio of two size pebbles is 1:1. Related performance test is ongoing. The Be pebbles with diameter of 1.0mmhave a very smooth external surface (Fig.16-17). The pebbles under the optical microscopy show an almost fully dense metallographic structure. Density of beryllium pebble measured by pycnometer is about 98% of theoretical density. Table 2 shows the chemical composition of the beryllium pebbles. The purity of the pebbles depends essentially on the Be electrode used.

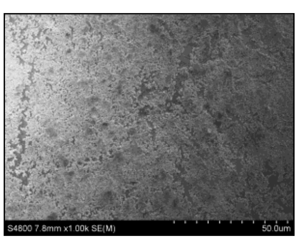


Fig.15 Surface of the Be pebble

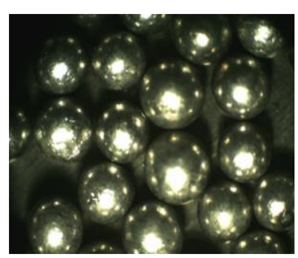


Fig.17. Be pebbles produced by REP

TABLE 2. CHEMIEALCOMPOSITIONS OF Be IMPURITIES (wt. %)

Element	BeO	C	Fe	Al	Mg	Si	Other impurities

Content,(wt. %)	0.90	0.12	0.07	0.03	<0.01	0.02	<0.04

The fabrication of Be pebble bed container and performance experiment of Be pebble bed have being implemented. The specific surface measured by multipoint Brunauer-Emmett-Teller (BET) methods using nitrogen gas is 5.05×10^{-3} cm^2/g.

A small-type Helium Gas Testing Loop (HGTL) is under construction as shown in Fig.9, which will be used for the future component testing and operation testing. The design temperature is 300℃ and the pressure of He gas is 8MPa. The layout of the HGTL loop was shown in the Fig.18.

Fig.18 Layout of HGTL loop

4. Interface design with ITER facility

Chinese HCCB TBM will be tested in Port No.2 of ITER test ports with the India Liquid Lithium Ceramic Breeder (LLCB) TBM simultaneously. Two TBMs and its associated ancillary systems will be integrated on same Port as well as interfaced with ITER buildings and sub-systems (Figs.19-20). The design and fabrication of related ancillary system are being performed.

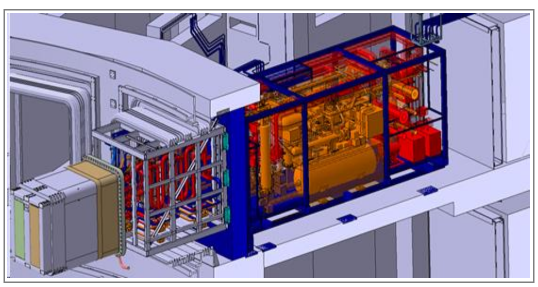


Fig.19. Integrated design for AEU in Port Cell

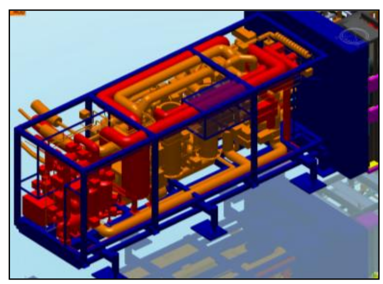


Fig.20 Pipes arrangement with IN TBM at AEU

China has signed the CN HCCB TBS arrangement (TBMA) with ITER international Organization (IO) in Jan. 2014, and the HCCB TBS conceptual design review (CDR) procedure have been completed in July 2014. The test plan and delivery schedule of CN HCCB TBS are scheduled based on ITER baseline. Chinese HCCB TBS test will be implemented with the cooperation of ITER IO, international institutions and industrial community.

5. Summary

The current progress on the updated design of the Chinese HCCB TBM and corresponding performance analyses were reported. Calculation and analyses results show that the modified HCCB TBM design is feasible and can be developed with the existing domestic technologies. Further work on the Chinese HCCB TBM module and system design will be carried out and the corresponding optimization design of the structure design as well as ancillary subsystem parameters are selected based on the ITER operation condition and testing limitations. Related R&D on the structure material (CLF-1), functional materials including Li_4SiO_4, neutron multiplier Be pebble, medium-sized mock-up of the first wall and the sub-module components are in progress. Small-sized (1:3) mockups of sub-module and components have been completed.

Acknowledgement

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