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Current progress of Chinese HCCB TBM program

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HIGHLIGHTS

- China plan to test own test blanket modules (TBM) during ITER different operation phase (H-H,D-D, D-T).
- A preliminary design (PD) of HCCB TBM have being performed since 2014.
- In order to reduce the effects of magnetic field ripple, the HCCB TBM design has been updated with reduced RAFM mass.
- Related R&D on key components fabrication, welding technology, materials development, He test loop constraction and mock-up test of TBM modules and components have being implemented.
- The current status on design and related R&D, as well as the development of auxiliary system (TES, CPS,HCS, etc.,) of Chinese HCCB TBS program ware overviewed.

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ABSTRACT

ITER is an unique opportunity to test tritium breeding blanket mock-ups in integrated Tokamak operating conditions. Helium-cooled ceramic breeder (HCCB) test blanket module will be the primary option of the Chinese ITER TBM program. China plans to test its own test blanket modules (TBM) during ITER different operation phase (H-H,D-D, D-T). A preliminary design of HCCB TBM have been completed in 2013. In order to reduce the effects of magnetic field ripple, the HCCB TBM design has been updated with reduced RAFM mass recently. Related R&D on key components fabrication, welding technology, materials development and mock-up test of TBM modules and components have being implemented. In this paper, the current status on design and related R&D, as well as the development of auxiliary system (TES, CPS,HCS, etc.,) of Chinese HCCB TBS program were introduced.

1. Introduction

Chinese helium cooled ceramic breeder (HCCB) test blanket system (TBS) will be tested in ITER to verify the related DEMO blanket technologies. The Chinese HCCB TBM Agreement (TBMA) has been signed at the beginning of 2014. Based on the requirement of this agreement, the conceptual design of CN HCCB TBS has been completed and reviewed by ITER in July 2014 [1,2]. The updated design of TBM module is ongoing based on preliminary design review (PDR) requirement.

In order to validate the design of CN HCCB TBS, a lot of R&D has been performed according to the technical requirements. The RAFM material Chinese Low Activation Ferritic (CLF-1) steel has been developed and is scaled to 5 ton ingot, which is used for the structure material certification. At the same time, the 1 dpa neutron irradiation test in high flux test reactor and its PIE experiment has been performed. Based on the CLF-1 steel, some component samples have been fabricated by the different fabrication techniques and tested. The 1/3 mockup of TBM module is under fabrication and will be tested soon. The fabrication techniques for the functional

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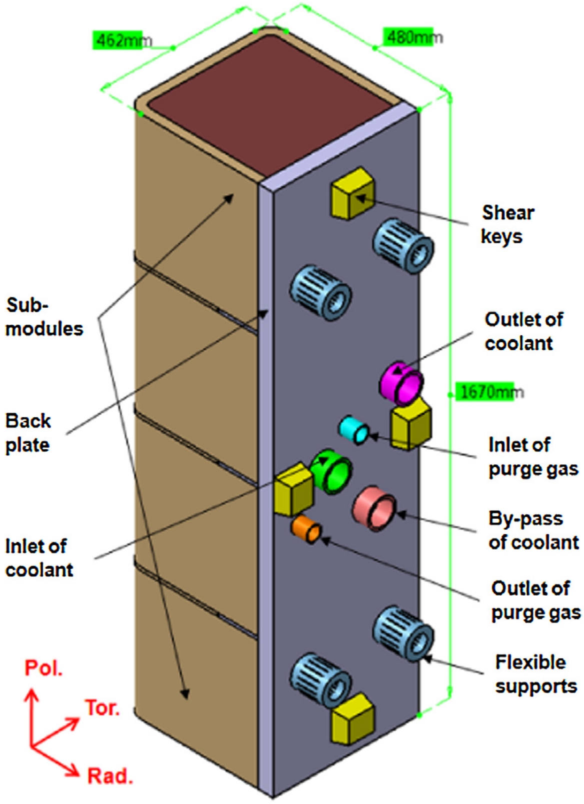

Fig. 1. Isometric view of CN HCCB TBM.

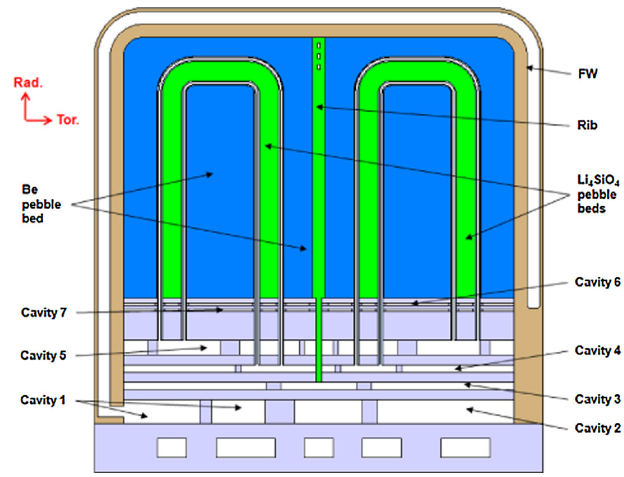

Fig. 2. Cross section view of CN HCCB TBM-set.

materials, such as beryllium and Li_4SiO_4, have been also developed and the related properties have obtained. The small-type Helium Gas Testing Loop (HGTL) is under construction, which will be used for the future component testing and operation testing.

Based on the current R&D status of CN HCCB TBS, the R&D plan has been proposed to support the preliminary design (PD) of CN HCCB TBS. After the completion of PD, final design (FD) will be started till 2019. Manufacturing process of CN HCCB TBS and delivery to ITER site are expected in 2023. Current CN HCCB TBMA milestones are based on the current ITER construction, and operation plan. CN HCCB TBS Milestones may be adjusted according to the update of ITER plan.

2. Updated design

A series of the Chinese HCCB TBS design have been carried-out since 2004 within the space limitation and technical requirements specified by ITER. The last structural design scheme for CN HCCB TBM is 2×6 configuration [1], in which 12 sub-modules packed with Li_4SiO_4 and Be pebbles are inserted in the TBM pressure component Box that is consisted of the First Wall (FW), caps, grid and back plate system. This scheme is quite complicated in structure, which also has produced influences up on the neutronics performance, and that the total mass of RAFMs material is about 1.7 tons which is much overweight compared with the limited value of 1.3 tons [3] given by ITER Organization in view of the magnetic field ripple factor in toroidal.

The updated design of CN HCCB TBM with 1×4 configuration scheme is shown in Fig. 1, it includes 4 independent breeding sub-modules with 10 mm gap (for thermal expansion) between each other along the poloidal direction, these sub-modules are connected with the back plate (that includes the auxiliary connection pipes for coolant and purge gas, shear keys and flexible supports) to form a whole TBM. And TBM is connected to the Helium Cooling System (HCS) and Tritium Extraction System (TES) by means of pipes in the big back plate.

Fig. 2 is the cross section view of Chinese HCCB TBM, in the front of breeding zone of sub-module, there are 2 symmetrical U-shaped Li_4SiO_4 pebble beds and the surrounding Be pebble bed, which are distributed in between the structural parts of sub-module including the U-shaped First Wall (FW), 2 caps in top and bottom, middle rib, 4 U-shaped cooling plates of breeding zone and 4 baffles (to separate the Li_4SiO_4 and Be pebble beds in top and bottom), etc. The rear part of Fig. 2 is the manifold of coolant and purge gas of sub-module, where the Cavity 1 is used to distribute the coolant from the back plate to the 8 internal coolant channels of FW (each channel consists of 3 identical parallel U shaped sweeps); Cavity 2 is to collect the coolant from FW and distribute it to the Cavity 3 and by-pass (to adjust the outlet temperature of breeding zone with about 500 °C); Cavity 3 is to distribute the coolant to the internal coolant channels of caps and rib; Cavity 4 is to collect the coolant from caps and rib and distribute it to the internal coolant channels of U-shape cooling plates; Cavity 5 is to collect the coolant of U-shape cooling plates and converge to the back plate then flowing into the HCS by the outlet of coolant; and Cavity 6 and Cavity 7 are used to distribute and collect the purge gas for the Li_4SiO_4 and Be pebble beds of sub-module.

As another important part of HCCB TBM-set, TBM shield provides shielding from fusion neutron radiation, gamma radiation, which will reduce neutron impact on Toroidal Field Coils (TFCs) and the other components behind TBM-set to acceptable level, and meanwhile provides vacuum boundary together with TBM frame and other internal components in ITER. Conceptual design of TBM shield has been finished, including 3D mechanical design and thermal-mechanical analysis [4,5].

The shield block consists of the flange, plates, caps and pipes, and there are several keys, flexible supports and electrical connections between TBM module and TBM shield, in order to fix the position and prevent large distortion caused by EM force, etc., as shown in Fig. 3. For better neutron shielding effect, several 60–75 mm thick parallel plates are used, with ~120 mm distance between each other, and the gaps among flange, plates and caps are all filled with water coolant, so that high-speed neutrons could get enough moderation [6].

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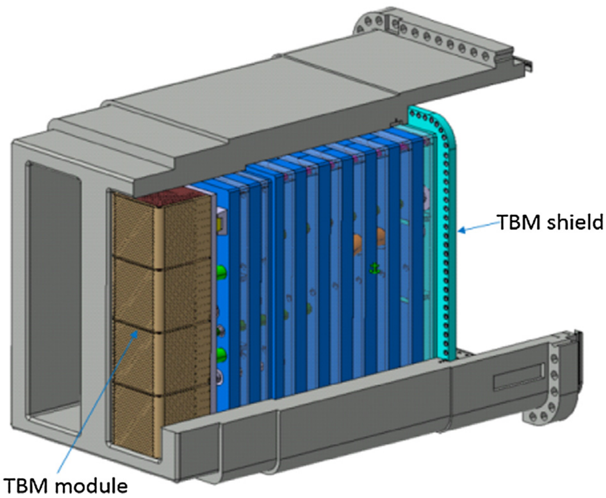


Fig. 3. Schematic view of HCCB TBM-set.

3. Preliminary analysis

3.1. Thermo-hydraulic analysis

A 3-D neutronics calculation for the updated TBM module design has been completed. Related results, neutron flux distribution and nuclear heat deposition are as input data of the thermo-hydraulics.

In the preliminary thermo-hydraulic analysis, a simplified analysis model for the sub-module of TBM is adopted, as shown in Fig. 4, in which top 6 layers of coolant for U shaped cooling plates, 2 layers of coolant for FW, full coolant of cap and part of rib are included, and there is a total of about 3.98 million mixed elements in the mesh model.

Thermal loads include the surface heat flux of 0.3 MW/m^2 on the facing plasma front of FW (from 0.3 MW/m^2 to zero loaded on the 2 circle chamfer faces of FW), and the different power density in the solid domains that is given by the neutronics analysis [7]. For the fluid domain, the mass flow rates for 2 inlets of FW are 3.01×10^{-2} and 3.27×10^{-2} kg/s with temperature 300 and ~354 °C, that for inlets of cap and rib are 2.28×10^{-2} and 1.83×10^{-3} kg/s with ~384 °C, and the mass flow rates between 5.50×10^{-4} and 8.37×10^{-4} kg/s with ~405 °C are specified on the 24 inlets of U shaped cooling plate, which are based on the reference [8] for hydraulic analysis results of coolant manifold system.

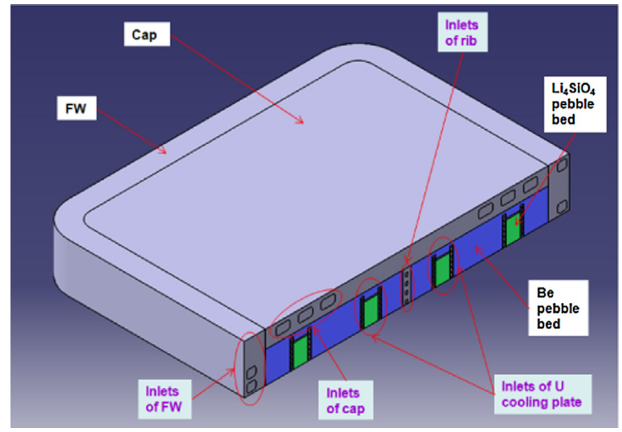


Fig. 4. Simplified thermo-hydraulic analysis model of sub-module.

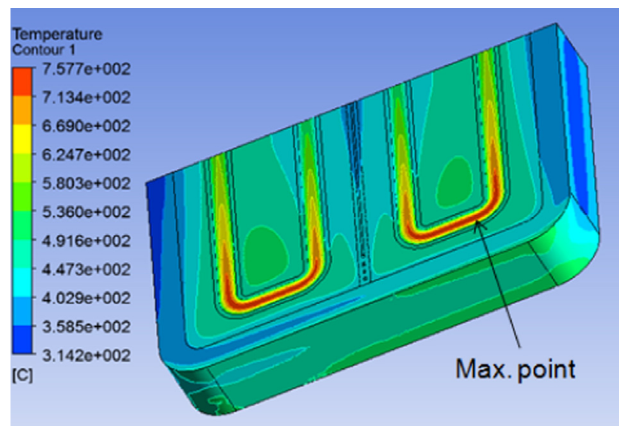
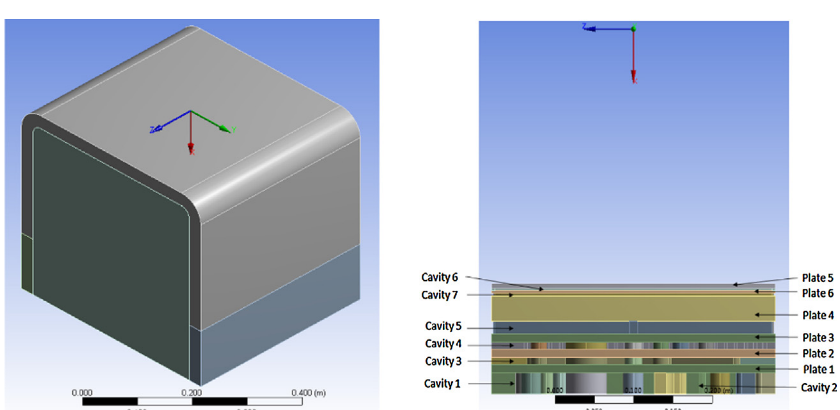


Fig. 5. Temperature distribution of sub-moudle.

Thermo-hydraulic analysis result for the temperature distribution of sub-module is shown in Fig. 5, it can be seen the high temperature regions of sub-module occur in the top of 2 U-shaped Li_4SiO_4 pebble beds, with the maximum value of 758 °C, comparatively, the maximum temperature of Be pebble bed is only 507 °C, and that of RAFMs structural parts is 534 °C located in the top corner edge of FW, which are all under their allowable temperature limits of 920 °C, 650 °C and 550 °C.



a)Global *b) Manifold*

Fig. 6. Structural analysis model for the Box of sub-module.

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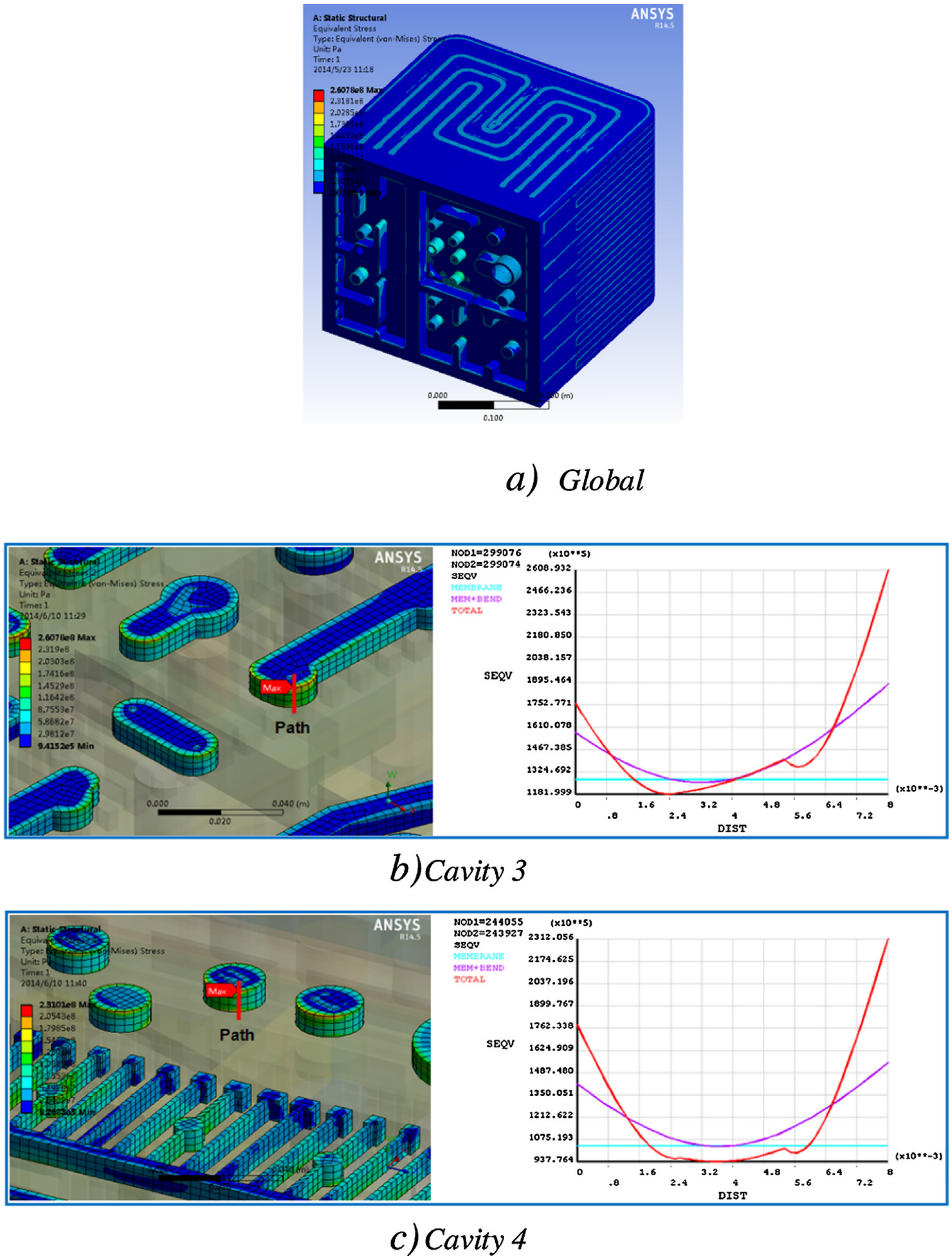
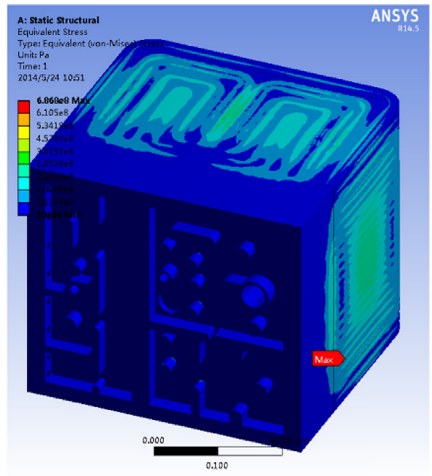


Fig. 7. Equivalent primary stress of Box under normal operation.

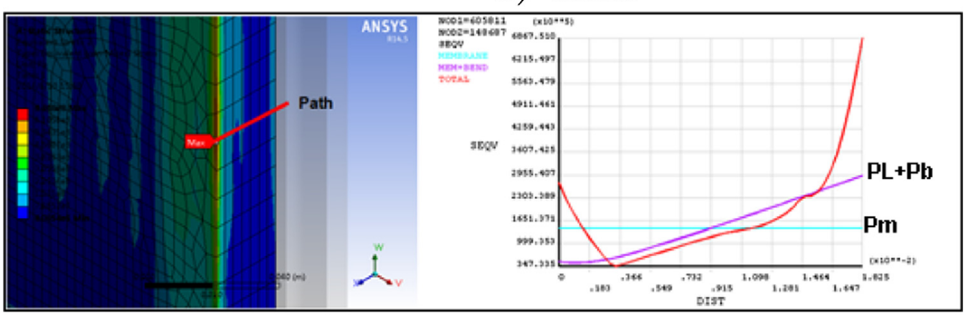
3.2. Structural analysis

The Box assembly (consisted of FW, caps, rib and manifold system) of sub-module is a pressure component, which is very important for the sub-module under both the normal operation and In-box Loss-of-coolant Accident (LOCA) conditions. The design for Box assembly of sub-module has to meet the primary stress (against P-type damage) requirements firstly. Analysis model of Box assembly is shown in Fig. 6a, which has the outer dimensions of 430 mm (radial, X axial) × 462 mm (toroidal, Y axial) × 410 mm (poloidal, Z axial) same with that of sub-module, where the manifold is the PL + Pb most complicated part with the multi plate-cavity structure, as shown in Fig. 6b. Thermo-mechanical properties of Reduced-Activation Ferritic/Martensitic steel, and CLF-1 [9] are used in analysis with regards to the criterion RCC-MR 2007 [9].

The gravity acceleration (9.81 [m/s^2], along Z direction) has been included in the analyses in order to take into account the dead weight of all the parts of Box. Compared with the load of dead weight, the pressure is the most important and dominant load in the FE analysis of Box against P-type damage. Under normal operation, there are 2 kinds pressure load including the design pressure of 10 MPa for the coolant surfaces and 0.3 MPa for the purge gas surfaces. Under In-box LOCA accident, the pressure load is only one 8 MPa (normal operating pressure of coolant), but which will distribute all the surfaces of coolant and purge gas. For the boundary condition of Box in the FE analysis against P-type damage, it is assumed that all the rear surfaces of Box connected with the big back plate are completely rigid, which an Equivalent stress analysis results for the Box assembly under normal operation is shown in Fig. 7a. It can be seen that the global equivalent stress is not high, the maximum total stress of Box is 261 MPa that locates in the root position of stiffening plate of coolant Cavity 3. Another high total stress of 231 MPa occurs in the same position of coolant Cavity 4, and the detailed linearized stress results for them are shown in



a) Global



b) Cap

Fig. 8. Equivalent primary stress of Box under In-box LOCA acciden.

Fig. 7b and c respectively. It is observed that the linearized stress results of both Cavity 3 and Cavity 4 meet the material allowable stress requirements Sm/1.5 Sm at 500 °C (148/222 MPa) based on the France criteria of RCC-MR 2007 [10].

Compared with normal operation, the pressure load of 0.3 MPa is replaced by that of 8 MPa in all the surfaces of purge gas under In-box LOCA accident, and the front part of Box will have obvious bulge deformation, which leads to the stress in the front part of Box rising significantly. The global equivalent stress distribution is shown in Fig. 8a, and the maximum total stress of Box under In-box LOCA accident highly attains to 687 MPa located in the root of cap, where is the area of stress concentration thus the peak stress accounts a large share of the total stress, and its relative linearized stress result is shown in Fig. 8b, which could meet the material allowable stress requirements $Sm^D/1.5\,Sm^D$ at 500 °C (280/420 MPa) based on the Category IV (Level D) in above criterion.

Fig. 9. Cuting process of 304 steel for U-shaped cooling plate.

4. R&D activities

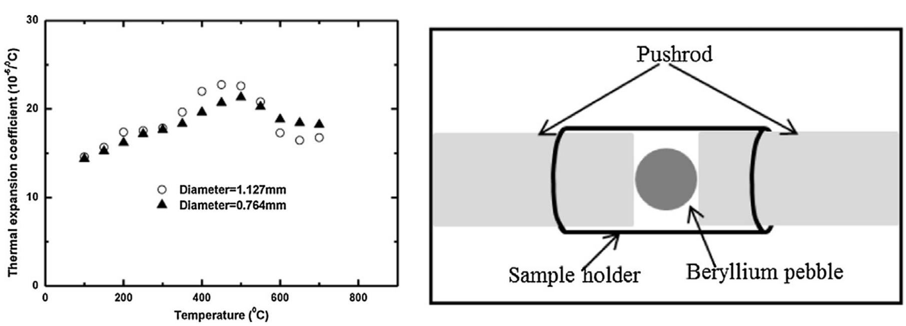
4.1. Mock-up of sub-module

Chinese HCCB TBM is a very complicated component, which mainly includes the 3 key parts which are the FW, U-shaped cooling plate and back plate system. For the manufacturing solution of FW, Hot Isostatic Pressing (HIP) is a realistic future process, and the base welding experimental researches for the HIP of RAFMs CLF-1 are being carried out to prepare for the next forming welding practices of FW at present. For that of U-shaped cooling plate, a special mechanical method is to be considered and researched to fabricate cooling plate. Fig. 9 is the preliminary attempt with the 304 steel using this process, in which the dimensional accuracy of rectangle hole of U-shaped cooling plate is good, it is ready to carry out the further experimental researches for CLF-1 steel using SE process in the first step of for fabricating U-shaped cooling plate. The fabrication of back plate system could be the current largest challenge for HCCB TBM; it is needed to explore the possible technologies actively.

Several welding technologies and manufacture process are carried out on the different sized plates, including Laser Welding (LW)

Fig. 10. HIP welding process.

Fig. 11. The elctronic beam welding for Big-PB and shield block.



(b) Thermal expansion coefficient. a) A sketch of thermal expansion test

Fig. 12. Thermal expansion coefficient of beryllium pebbles.

process for the BP and the FW, HIP welding for FW that is shown in Fig. 10. The electronic beam welding for big-BP and shield block is shown in Fig. 11. The welging of the CLF-1 with the 316 LN IG (ITER Grade) is dissimilar welding process for assembling TBM module and shield block. Some tests on the welding are assessing.

4.2. Function materials development

The thermal expansion coefficient of two kinds of Be pebbles are measured with horizontal pushrod dilatometer (DIL 402 PC, NETZSCH). A schematic of the thermal expansion test is shown in Fig. 12a. The sample hold is made of Al_2O_3.

The thermal expansion coefficient of the beryllium pebble is shown in Fig. 12(b). The thermal expansion coefficient of larger pebble almost corresponds to that of smaller pebble. It is clear from these data that the the coefficient of expansion of beryllium pebble increases with the temperature in the temperature range of 100–550 °C. The coefficient of thermal expansion of beryllium pebble slightly decreases when the temperature is large than 550 °C. The decrease may be related with the crystal axis direction. The beryllium crystal has an anisotropic slip characteristic and the thermal expansion will be released by anisotropic slip.

The mechanical behavior of a significant number of pebbles with two diameter have been investigated by submitting them to compressive loads up to 2000 N at room temperature. The sample is compressed by the rod with a compression speed of 0.05 mm/min. The plastic deformations of the pebbles have been measured and correlated with the applied loads as shown in Fig. 13. For two kinds of pebbles, the load curve is relatively smooth. However, a small change is observed at the compression load about 250 N. The compression load is obviously reduced presumed to be due to a crack formation. The tested sample is not separated into many parts up

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to 2000 N and only one big crack parallel to the compressive force direction is observed. It is observed that the fracture properties of the beryllium pebbles are not affected by pebble size.

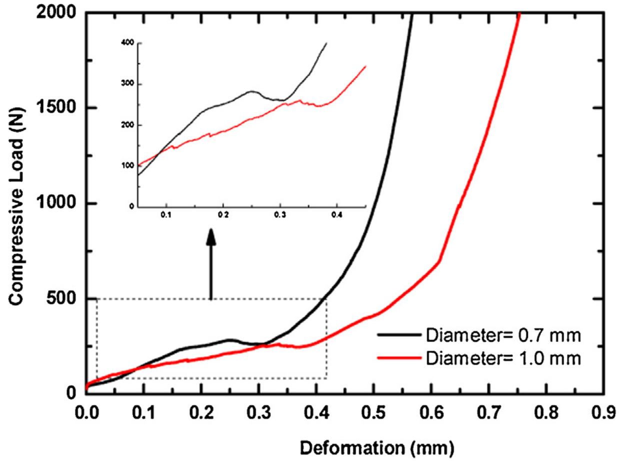

Fig. 13. Deformation of the Be pebbles for various applied mechanical loads.

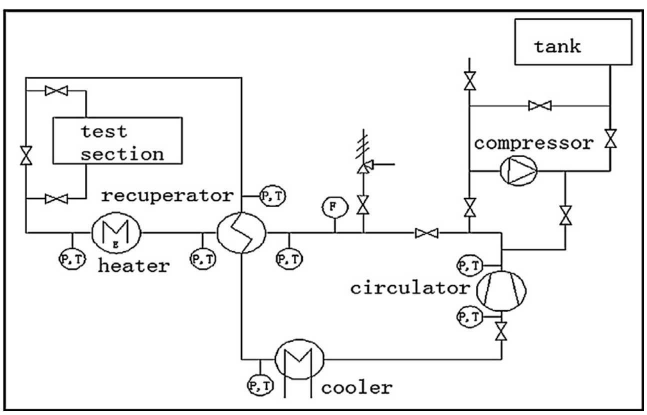

Fig. 14. Flow diagram of HGTL.

Fig. 15. Layout of HGTL test loop.

4.3. Helium gas test loop

In order to vilidate the fluid properties of HCCB TBM module, a small Helium Gas Test Loop (HGTL) is under construction in SWIP. The flow diagram of HGTL is shown in Fig. 14. The design temperature is 300 °C and the pressure of He gas is 8 MPa. A diaphragm type compressor is used as circulator, with a flow rate of 0.1 kg/s. Recuperator and cooler are tube shell type heat exchanger. A 200 kW heater is used for heating helium. A compressor and tank are used for helium supply and storage. Because of the small flow rate of diaphragm circulator, a centrifugal blower is considered as circulator for next step. Fig. 15 shows the layout of HGTL.

5. Summary

The TBM program will be an important part of China fusion development Strategy. The HCCB TBMA has been signed between ITER international organization (IO) and Chinese domestic agency (CNDA). The conceptual design review (CDR) has been hold in 2014. The design of HCCB TBS is developing in details according to the ITER schedule. R&D has been made progress on development of structure material, fabrication of function materials (ceramic tritium breeder, neutron multiplier Be pebble), medium-sized mock-up of first wall, components and sub-module. The R&D and test plan, delivery schedule of Chinese HCCB TBS are scheduled. Chinese HCCB TBM test will be implemented with the cooperation of domestic and international institutions and industries.

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