Overview of Design and R&D of solid breeder TBM in China

K.M. Feng[1)], C.H. Pan[1)], G.S. Zhang[1)], T. Yuan[1)], Z. Chen[1)], Z. Zhao[1)], H.B. Liu[1)], Z.Q. Li[1)], G. Hu[1)], X.Y. Wang[1)], X.F. Ye[1)], D.L. Luo[2)], C.M. Gao[4)], T.Y. Luo[1)], Y.J. Feng[1)], H.Y. Wang[2)], Y.J. Chen[1)], Z.W. Zhou[3)], Z. X. Li[1)], G.Y. Zheng[1)], Q.J. Wang[1)], Q.X. Cao[1)], T.F. Hao[1)], L.H. Ma[1)], B. Xiang[1)], L. Zhang[1)], F.C. Zhao[1)]

[1)] *Southwestern Institute of Physics, Chengdu 610041, P.R.China*
[2)] *Institute of Engineering Physics, Chinese Academy of Science, P.R. China*
[3)] *Tstinghua University, Beijing 100084, P.R.China.*
[4)] *University of Electronic Science and Technology of China, Chengdu 610054, P.R. China*
Email: *fengkm@swip.ac.cn; Fax:+86-28-82850956*

Abstract

Testing TBM (Test Blanket Modules) is one of important engineering test objectives in ITER project. China is performing the TBM design and R&D based on Chinese development strategy of fusion DEMO. Helium-cooled test blanket module concept with ceramic breeder for testing on ITER will be one of the basic options in China. The current progress and status on design and R&D of CH HC-SB (Chinese Helium-cooled Solid Breeder) TBM are introduced briefly in this report. The modified designs of HC-SB TBM, related ancillary sub-systems and test strategy on ITER as well as relevant R&D activities are summarized.

1. Introduction

Testing TBM (Test Blanket Modules) is one of important engineering test objectives in ITER project. China is implementing the TBM design and R&D plan based on Chinese development strategy of fusion DEMO [1-2]. Helium-cooled test blanket module concept with ceramic breeder for testing during ITER operation period will be one of the basic options in China. Different design of HCSB TBM on module size, sub-module arrangement and modification and optimization of system have been carried out since 2004.

The current progress and status on design and R&D of CH HC-SB (Chinese Helium-cooled Solid Breeder) TBM are introduced. The modified designs of HC-SB TBM and related ancillary sub-systems, test plan on ITER and relevant R&D activities are summarized. An international and domestic collaboration plan on R&D and construction of related facilities of TBM are proposed.

Under the cooperation of domestic institutes, the preliminary design and performances analysis as well as an updated Design Description Document (DDD) have been carried out in 2007. Preliminary design and analysis have shown that the proposed TBM module concept is feasible within the existing technologies.

2. Design Description

A modified design of the HC-SB TBM based on 2×6 sub-modules arrangement and 3-D global neutronics calculation have been completed [3]. The structure design outline of CH HC-SB module based on “half-port” size of ITER test port is described. The HCSB-TBM is located in vertical frame of the equatorial test port. Dimension of the frame is 1700mm in poloidal direction, 524mm in toroidal direction and 800mm in radial direction. Taking into account 20mm gap between TBM and frame, the dimension of HCSB-TBM is 1660mm height and 484mm width. Facing plasma side of HCSB-TBM is needed to be protected by beryllium layer of 2mm. the radial dimension of the HCSB-TBM is 670mm except for beryllium layer thickness. The HCSB-TBM consists of the following main components: U-shaped first wall, caps, back-plate, grid, breeding sub-modules, and support plate. The details of HCSB-TBM are illustrated in figure 1.

The Reduced-Activation Ferritic/Martensitic (RAFM) steel and the helium gas are used as structure material and coolant, respectively. To assure an adequate tritium breeding ratio (TBR), beryllium pebbles with diameters of 0.5-1mm with pebble-bed structure are adopted as neutron multiplier; The lithium orthosilicate (Li_4SiO_4) with enriched lithium-6 of 80% is used as tritium breeder. The pressure of the helium cooling system and the tritium extraction system are 8MPa and 0.1 MPa, respectively. The explosive view of HCSB TBM and the cross-section of sub-module are shown in Fig.1-2. Main parameters of the HCSB TBM design are shown in Table 1. Comparing with others TBM designs [4-5], Chinese solid TBM have obvious characteristics of simple structure, mature technical in domestic.

Table 1 Main parameters of the HCSB TBM design

Neutron surface loading, [MW/m^2]	0.78
Surface heat flux,[MW/m^2]	0.5
Total power (includes surface heat flux), [MW]	0.99
Tritium production ratio, [g/FPD]	0.0127
Tritium breeder Form ^6Li enrichment, [%] Max. temperature, [℃]	Lithium orthosilicate, Li_4SiO_4 Ø=0.5-1mm, pebble bed 80 693
Neutron multiplier Form Max. temperature, [℃]	Beryllium Binary, Ø=0.5-1mm, pebble bed 635
Coolant	(He)
Pressure, [MPa]	8
Temperature(inlet/outlet), [℃]	300/500
Pressure drop, [MPa]	0.3
Structure material Max. temperature, [℃]	Ferritic steel, CFL-1 528

The tritium exaction system (TES), helium-cooling system (HCS), and the coolant purification system (CPS) have been designed as auxiliary systems. Main design parameters for the tritium extraction system (TES) are as follows: the composition of purge gas is He+ 0.1%H_2, pressure at the inlet of TBM blanket is 0.12 MPa, extracted amount of tritium is 0.1 g/d, helium mass flow is 0.65 g/s, and tritium extraction efficiency ≥95%.

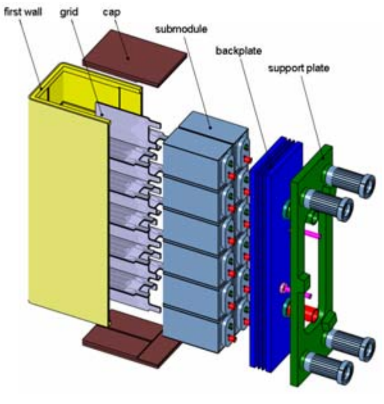

Fig.1 Explosive view of the HCSB-TBM

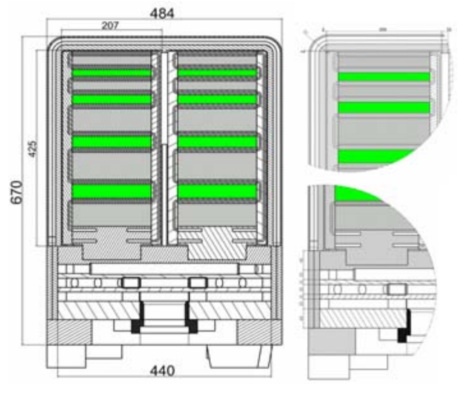

Fig.2 Cross-section of Sub-module

3. Performance Analysis

3.1 Neutronics Analysis

Three-dimensional neutronics calculation based on the ITER-FEAT structure model using MCNP/4C [6] code and the data library FENDL2.0 [7] give the total energy deposition of 0.567MW, and a peak power density of 5.85 W/cm^3 under a neutron wall loading of 0.78 MW/m^2. The 3-D model of neutronics calculation is shown in Fig.3. The power density distribution in the radial zone is shown in Fig.4. The tritium generation amount is 0.0127g for a full power day (FPD). In order to improve the power density in the blanket module, the arrangement of the Be neutron multiplier in the breeding zone has been optimized. Binary Be pebbles with diameter 0.5 and 1 mm were are chosen.

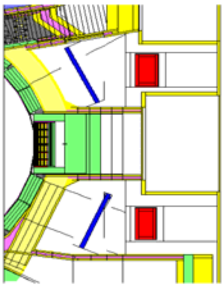

Fig.3 The MCNP model of neutronics calculation

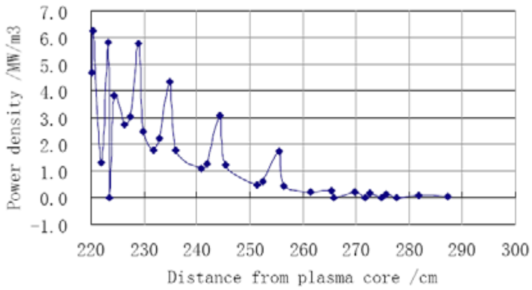

Fig.4 Power Density distribution in the radial zones

3.2 Thermal-hydraulics

For the CN HCSB TBM, the inlet and outlet temperature of the helium coolant is 300 ^{0}C and 500 ^{0}C, respectively. The serial connection scheme is adopted in the coolant flow loop of TBM, that is the coolant flows into the first wall, cap/grid, and the sub-module in series. The thermal-hydraulic analysis is performed using the ANSYS [8] and FLUENT codes. The results show that, under the extreme operative condition with a surface heat flux of 0.5MW/m^2, the peak temperature of TBM amounts to 693 ^{0}C which occurred in the second breeder zone of sub-module, and the peak temperatures of different zones (listed in table 1) are in permissible range of different materials (700 ^{0}C for Be, 550 ^{0}C for ferritic steels and 900 ^{0}C for ceramic Li_4SiO_4). The temperature distributions of first wall, cap/grid, and sub-module are shown in Figs.5-8.

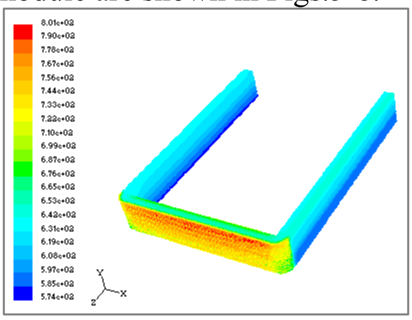

Fig.5 Temperature distribution of first wall

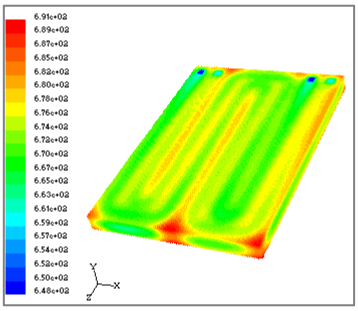

Fig.6 Temperature distribution of cap

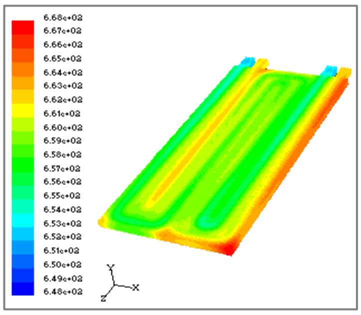

Fig.7 Temperature distribution of grid

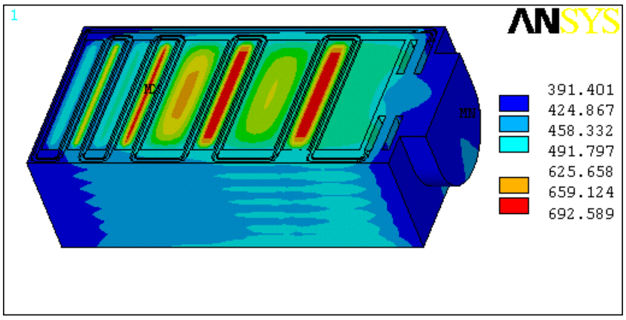

Fig.8 Temperature distribution of first wall

The pressure drop in the TBM is about 0.3MPa. The estimated pressure drop in the TBM external circuit is about 0.1MPa, assuming the total length is 100m, the inner diameter is 100mm and 20 bends 90° are included for the hot and cold leg, respectively. So the total pressure drop in the TBM helium circuit system is about 0.4MPa and the needed pumping power is 100KW assuming the pump efficiency is 80%.

3.3 Radioactivity Calculation

Activation analysis has been performed assuming a continuous irradiation over 1 year at full fusion power (500 MW). Neutron fluxes are provided in46 energy groups by 3-D neutron transport code MCNP for each specified material zone. Activation and dose calculations are performed by means of computation codes FDKR [9] and DOSE. The composition data of structure material in the module is from reference material EUROFER97. The results show that the total activation inventory is 7.86×10^{16} Bq at shutdown time and drops slowly thereafter and reaches an extremely low level value of 1.09×10^{13} Bq after 100 years. The dose rate is 3.34×10^{7}mSv/hr at shutdown time. Thereafter the dose rate declines rapidly and reaches 2.62mSv/hr after 10 years. Considering ITER operation factor 0.22, after 10 years' cooling, the dose rate is enough to meet ALARA threshold.

3.3 Safety Analysis

Preliminary safety analyses including LOCA, LOFA and accident analysis based on FMEA method have been completed by using FDKR, RELAP5 and DOSE codes.

The thermal-hydraulic safety analysis has to testify that the TBM and its Helium Cooling System (HCS) will not have a impact on the safe operation of ITER under normal and accidental conditions. In order to simulate the transient accidents, TBM and HCS are modeled using system code RELAP5/MOD3 [10]. The performance of the TBM and HCS during normal operation and accidents has been investigated [11-12]. Steady state and three postulated initiating events, In-Vessel LOCA, Ex-Vessel LOCA and In-Box LOCA ,are considered.

The Ex-Vessel LOCA will induce the melting of first wall beryllium armor after about 80 seconds of the LOCA initiation and some controlling measures have to be taken before melting. The pressurization of Vacuum Vessel induced by In-Vessel LOCA is about 26kPa, and it's within the allowable value of ITER design 200kPa. The variety of the temperature in Ex-Vessel LOCA and the variety of the VV helium pressure in In-Vessel LOCA are shown in Figs.9-10, respectively. The In-Box accident would lead to pressurization of the TBM box including all pebble beds and the pressure of purge gas pipes to the system pressure of 8MPa in about 2 seconds. So there must have a pressure relief for the blanket box, and at the same time the fast isolation of the TES from TBM has to be taken to keep the TES safety.

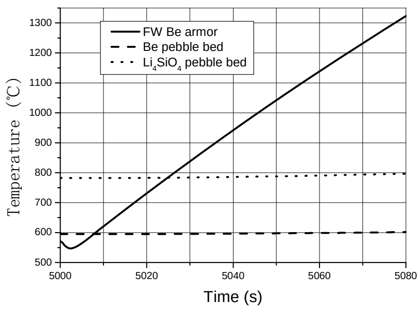

Fig. 9 Temperature in Ex-Vessel LOCA

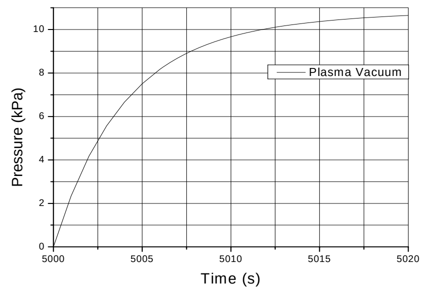

Fig.10 VV helium pressure in In-Vessel LOCA

4. R&D Progress

4.1 Heilium Test Loop

In order to validate TBM design, especially regarding mass flow and heat transition processes in narrow cooling channels, it is indispensable to test mock-ups in a helium loop under realistic pressure and temperature profiles [13]. According to TBM design parameters, requirements for the test section are summarized in table 3.

Table 3 Requirements for test sections

Test section	HE mass flow rate /kg^{-}/s	Pressure /MPa	Pressure difference at test section /MPa	He inlet/outlet temperature /℃	power supply /MW
TBM	0.13～1.3	8	<0.3	300/500	1
DEMO Blanket	～4	8	<0.4	300/500	5

The loop includes the primary helium heat transport loop and the secondary water loop. Main components of the primary loop are, besides the test module, a heat exchanger, circulator, electrical heater, dust filter, control valves and pipe work. The primary loop is directly connected to the helium purification subsystem via small pipes by taking a small bypass flow. Another interface to the pressure control unit is needed for system evacuation, helium supply and protection against overpressure. Thermal stress has been calculated by software CAESAR. Corrugated pipe is not used. If use it, the footprint will be smaller and the pipeline could be simpler.

The preliminary designs of the helium gas test loop with pressure 8-10MPa and temperature 550-600°C have been completed [11-12]. The flow chart of the test loop are shown in Fig.11. The layout diagram of the test loop is shown in Fig.12.

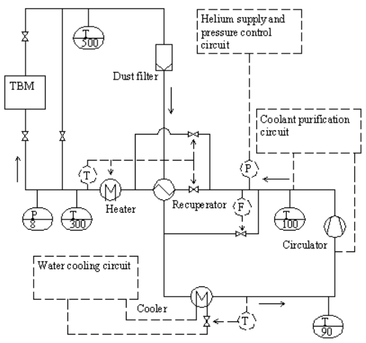

Fig.11 Flow chart of the test loop

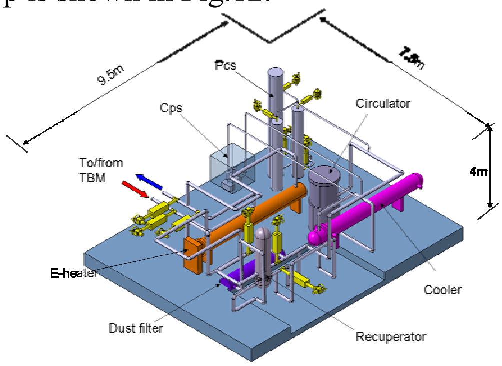

Fig.12 Layout diagram of the test loop

4.2 Ceramic Breeder

Investigation of two kinds of ceramic breeder, Li_2TiO_3 and Li_4SiO_4, on fabrication and performance test is undergoing in China. Relevant R&D on the key issues for the ceramic breeder, the tritium permeation barrier, is also introduced. The study on experimental technologies relative to pebble bed has also been started. The influence of pebble dimensions and filling factor on pebble bed properties have primarily been investigated. In order to study the heat transfer in the blanket, the experimental apparatus will be planed to design and measure the effective thermal conductivity of pebble beds. The foundational study on tritium behavior in solid breeder has been conducted with cooperation of the foreign universities. The sample of Li_4SiO_4 pebbles of diameter 1mm is shown in Fig.13.

Fig.13 Li_4SiO_4 pebbles of diameter 1mm

4.3 Neutron Multiplier

The fabrication of beryllium pebbles has been investigated. Rotating Electrode Process (REP) developed by NGK co. in EU [14] and Japan Gas Atomization Method (GAM) developed by Brush Wellman co. in USA are considered as candidate fabrication processes of beryllium pebbles for CH HCSB TBM.

The study on experimental technologies relative to pebble bed has also been started. We primarily investigated the influence of pebble bed dimensions and filling factor on pebble bed properties. In order to study the heat transfer in the blanket, the experimental apparatus will be planed to design and measure the effective thermal conductivity of pebble beds.

China has large yielding ability and relevant fabrication experiences of neutron multiplier (Be). Under the support of ITER Shielding Blanket Module (SBM) qualification task, development of Chinese VHP-Be is undergoing.

4.4 Structure Materials

Reduced Activation Ferritic/Martensitic (RAFM) steels are the reference structural materials for the in- vessel components of DEMO. Also, this type of materials will be used in the test blanket modules (TBM) to be tested on ITER test port. Chinese Low-activated Ferritic/martensitic steel, CLF-1, is being developed. The CFL-1 steel is used as the primary candidate structural material for Chinese HCSB TBM design.

The structural materials for the blanket must maintain their mechanical integrity and dimensional stability for adequate lifetimes under the severe radiation thermal, chemical and stress condition imposed in a fusion reactor environment. The candidate materials must be resistant to neutron radiation damage, capable to elevated temperature operation under stress, compatible with other blanket and plasma materials, compatible with the hydrogen plasma, and capable of withstanding high surface heat fluxes. The structural material must have adequate resources and be easily fabricated. In addition, the structural material should not produce high levels of long-lived radioactive products and that short-lived products should not produce unacceptable safety consequences. Some test results of CLF-1 are shown in Figs.14-15.

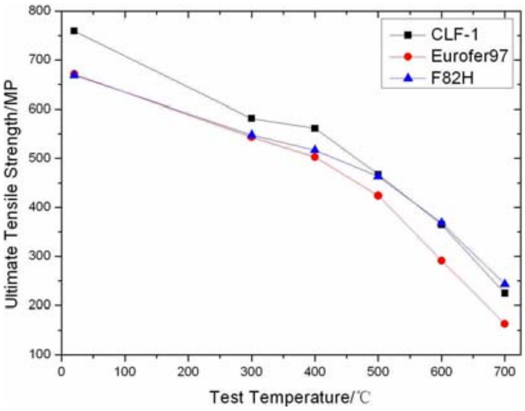

Fig.14 Tensile Strength of CLF-1

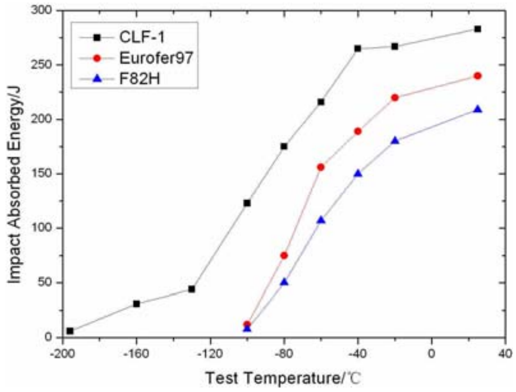

Fig.15 DBTT of CFL-1

5. Summary

A modification design and performance analysis of Chinese ITER HC-SB TBM has been completed. Preliminary design and performance analysis for the TBM module have been performed. The results show that the current design of HCSB TBM is feasible within the existing technologies. It is characterised by simple structure, mature technical in China. Updated design description document (DDD) of HCSB TBM has been carried out in 2007. The further design works will update and optimize the structure design as well as ancillary subsystem parameters. The fabrication technology of components and ceramic breeder for HCSB TBM are being developed in China.

References

[1] K.M. Feng, P.C Pan, G.S. Zhang, T. Yuan, Z. Chen, et al., Overview of design and R&D of solid breeder TBM in China, Presented at 8th International Symposium on Fusion Nuclear Technology (ISFNT-8), Heidelberg, Germany, , Sept.30-Oct.5, 2006.

[2] K.M. Feng, C.H. Pan, G.S. Zhang, D.L. Luo, Z.W. Zhou, et al., Preliminary design for a China ITER test blanket module, J. of Fusion Engineering and Design, 81(2006)1219-1224.

[3] PAN Chuanhong. Definition of DEMO reactor and DEMO development strategy in CH[R] Test Blanket Working Group Meeting (TBWG-12) Naka, Japan Mach 10-11, 2004.

[4] G. S. Hatalov, I. Kirillov, et al., Russian DEMO-S reactor with continues plasma burn [J] .Fusion Engineering and Design 51-52 (2000) 289-298.

[5] S. Nishio, T. Ando, et al., Engineering aspects of a steady state tokamak reactor [J] .Fusion Engineering and Design 15 (1991) 121-135.

[6] J. F. Briesmeister (ed.): MCNP - A General Monte Carlo N-Particle Transport Code, Version 4C, LA-13709-M, April 2000.

[7] H. Wienke and M. Herman, FENDL/MG-2.0 and FENDL/MC-2.0, The processed cross-section libraries for neutron-photon transport calculations, version 1, March 1997, IAEA Vienna, Report IAEA-NDS-176, Rev. 1, October 1998.

[8] ANSYS Technical Report, Rev. 5.1, IMAG Industries Co., February, 1995.

[9] Y.X.Yang, K.M.Feng and J.H.Huang, CCC-541/FDKR, Radiation Shielding Information Center, Oak Ridge National Laboratory, 1989.

[10] The RELAP5 Code Development Team: RELAP5/MOD3 Code Manual Volume I: Code Structure, System Models, and Solution Methods, NUREG/CR-5535, INEL-95/0174, Aug. 1995.

[11] Boccaccini L.V., Design Description Document for the European Helium Cooled Pebble Bed (HCPB) Test Blanket Modules, Forschungszentrum Karlsruhe, December, 2005.

[12] Jin Xuezhou, R.Meyder, Thermal-Hydraulic System Study of the Helium Cooled Pebble Bed (HCPB) Test Blanket Module (TBM) for ITER Using System Code RELAP5, Chinese Plasma Science and Technology, Vol.2 2005.

[13] Ionescu Bujor, M, et al., Helium Loop Karlsruhe (HELOKA) – large experimental facility for the in-vessel ITER and DEMO components, 20th IAEA fusion energy conference, 2005.

[14] K.M. Feng, G.S. Zhang, Z Chen, T, Yuan, Z Zhou, et al., Design Description Document for the Chinese Helium- cooled Solid Breeder (CH HCSB) TBM, (Draft Design Report), 2007.