Thermal Hydraulic and Mechanical Analysis of CH HCSB TBM

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Abstract: Based on the structure design and the result of neutronics analysis of the CH HCSB TBM (Chinese Helium Cooled Solid Breeder Test Blanket Module), the thermal hydraulic analysis and thermal mechanical analysis of the CH HCSB TBM have been carried out to confirm the feasibility for the normal conditions and extreme conditions in ITER NT operation phase using FE code ANSYS. It is confirmed that the design of the CH HCSB TBM is reasonable and acceptable.

1. Introduction

Test blanket module (TBM) is one of important components in ITER. CH HCSB TBM has been proposed. According to the proposed structure design, the neutronics analyses results of the CH HCSB TBM in ITER NT operation phase have been given [1]. Based on the heat loads conditions of the test blanket module and the results of neutronics calculation during ITER NT operation phase, thermal hydraulic analysis and thermal mechanical analysis of the CH HCSB TBM have been carried out for the normal conditions (neutron wall loading of 0.78MW/m^2 and surface heat flux of 0.3MW/m^2) and extreme conditions (neutron wall loading of 0.78MW/m^2 and surface heat flux of 0.5MW/m^2) using ANSYS code. The analysis results show that the temperature and stress distribution in the module are acceptable.

2. Model and Materials of CH HCSB TBM

According to the design, the CH HCSB TBM consists of the following main components: U-shaped First Wall (FW), cap, back plate, grid, and breeding sub-module shown in the Figure 1. The TBM module has 18 sub-modules separated by the grid. In the test module, FW comprises 87 pieces of cooling plates along poloidal direction. Each cooling plate has a cooling tube with 14 mm x 7 mm rectangle inner section. In order to increase heat transfer coefficient, channels of every three cooling plates are connected in series and become a flow path. As to 18 sub-modules, each sub-module has 25 pieces of cooling plates with 6mm diameter cooling channels along poloidal direction.

The CH HCSB TBM comprises multiplying and breeding material zones and structure material. In the test module, the coolant from inlet flows in the FW through manifold, then splits in 21 streams for 18 sub-modules, grids, top and bottom plates. The flow scheme of the test module is shown in Figure 2. This flow scheme can be optimized according to the thermal and structure analysis results.

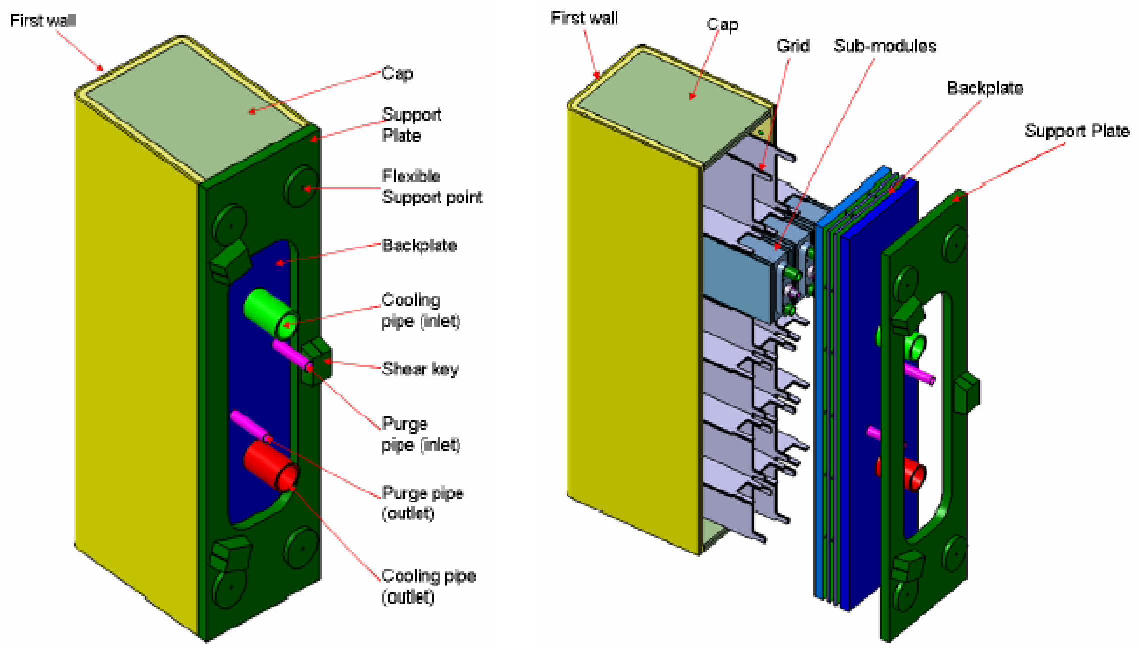


FIG. 1. CH HCSB TBM and its components

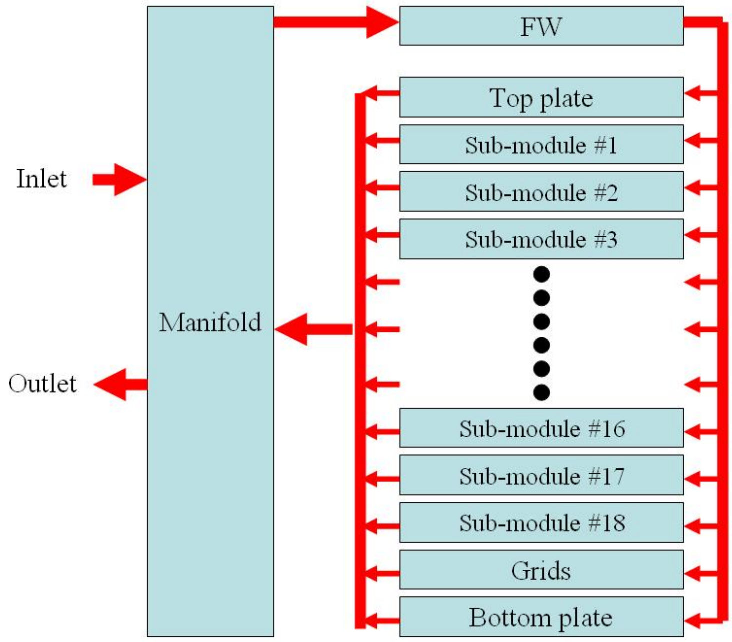


FIG. 2. Flow scheme of the test module

In the CH HCSB TBM, the ferritic steel (EUROFER) [2] is used as structure material. Beryllium [3] is used as armor of first wall. Multiplier and breeder are beryllium pebble bed [4] and lithium silicate pebble bed [5] respectively.

According to the design of the test module, FW comprises 87 pieces of cooling plates along poloidal direction, and channels of every three cooling plates are connected and become a flow path. So 1/3 FW segment model with 10 flow paths (including 30 channels in series) is modeled, and the thermal mechanical analysis has been carried on for different condition.

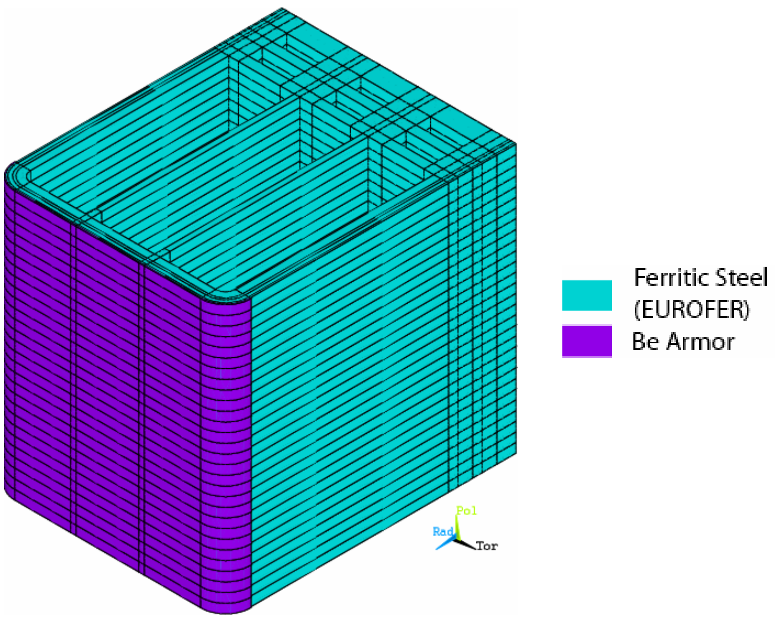


FIG. 3. FW model

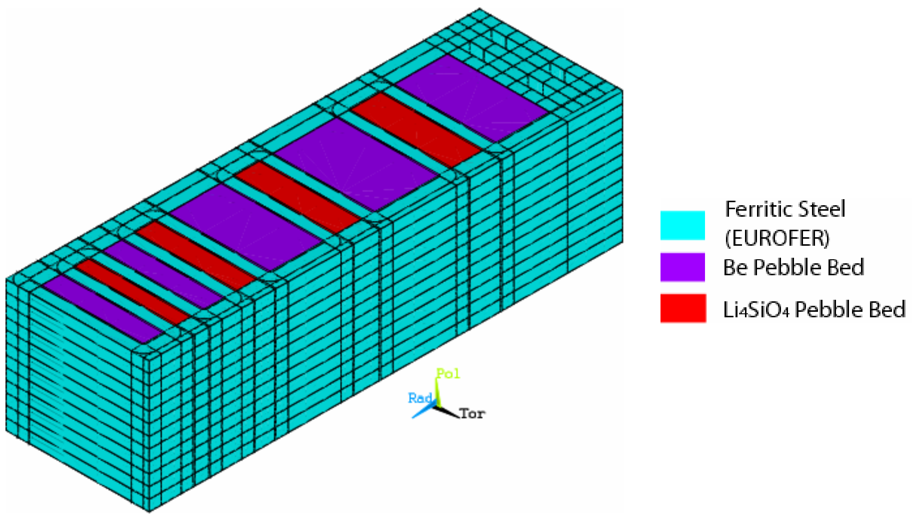


FIG. 4. Sub-module model (2D)

Each sub-module has 25 pieces of cooling plates along poloidal direction. So half sub-module is modeled in ANSYS and used to simulate (shown in Figure 3 and 4).

2. Thermal Hydraulic Analysis

2.1. Thermal Hydraulic Parameters

The nuclear heating power densities in the structure material, beryllium armor, breeder and multiplier are given by neutronics calculations (neutron wall loading of 0.78MW/m^2). The surface heat fluxes of first wall are 0.3MW/m^2 at normal conditions and 0.5MW/m^2 at extreme conditions. According to these results, thermal hydraulic parameters of test module are obtained through analysis and shown in Table I.

TABLE I: THERMAL HYDRAULIC PARAMETERS

	Normal condition	Extreme condition
Neutron surface loading [MW/m^2]	0.78	0.78
Surface heat flux [MW/m^2]	0.3	0.5
Helium pressure [MPa]	8	8
Helium inlet/outlet temperature [°C]	300/500	300/500
Max. power density in		
beryllium armor [MW/m^3]	8.41	8.41
beryllium pebble bed [MW/m^3]	3.17	3.17
lithium silicate pebble bed [MW/m^3]	8.96	8.96
structure material [MW/m^3]	6.50	6.50
Total power (surface heat flux included) [MW]	0.86	1.02
Power from surface heat flux [MW]	0.24	0.40
Power in		
beryllium armor [MW]	0.01	0.01
beryllium pebble bed [MW]	0.10	0.10
lithium silicate pebble bed [MW]	0.21	0.21
top and bottom plates [MW]	0.01	0.01
structure material [MW]	0.28	0.28
Total Mass flow rate of helium [kg/s]	0.83	0.99
Mass flow rate of helium in		
FW [kg/s]	0.83	0.99
single sub-module [kg/s]	0.04	0.05
top and bottom plates [kg/s]	0.03	0.03
Velocity of helium in		
FW [m/s]	51	61
sub-module [m/s]	11	13
Pressure drop of coolant in module [MPa]	0.17	0.24
Pressure drop in FW [MPa]	0.16	0.22
Pressure drop in sub-module [MPa]	0.01	0.02

Based on the thermal hydraulic parameters, the heat transfer coefficient (HTC) can be obtained and listed in Table II.

TABLE II: HEAT TRANSFER COEFFICIENT [W/m^2·K]

	Normal condition	Extreme condition
Heat transfer coefficient in FW	5028	5714
Heat transfer coefficient in sub-module	1425	1621

The temperature increases of coolant in different components are listed in the Table III.

TABLE III: TEMPERATURE INCREASES OF COOLANT IN DIFFERENT COMPONENTS

Component	Normal condition		Extreme condition	
	ΔT (°C)	Inlet/outlet T (°C)	ΔT (°C)	Inlet/outlet T (°C)
FW	95	300/395	111	300/411
Sub-module	105	395/500	89	411/500
Top, bottom plates and grids	105	395/500	89	411/500

2.2. Loads

Two kinds of plasma loads, surface heat flux on the first wall and heat generation due to neutron surface loading have been involved in the analyses. The surface heat fluxes on the first wall are $0.3MW/m^2$ for normal condition and $0.5MW/m^2$ for extreme condition. And heat generations of different materials come from neutronics calculation results.

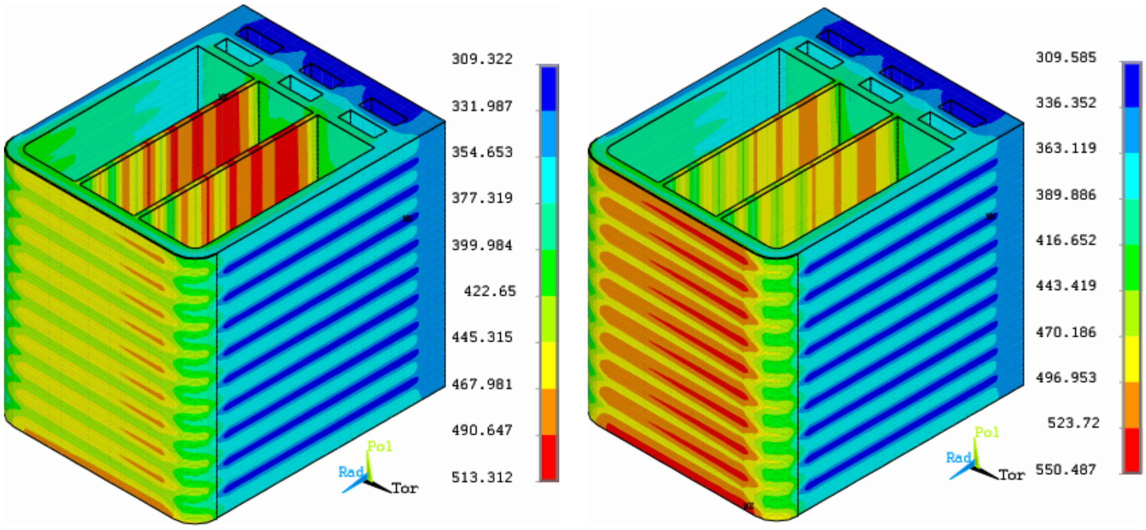
The heat transfer coefficient of coolant in FW and sub-module are listed in Table II and the bulk temperature of coolant is calculated by means of energy equation method.

2.3. Temperature Distribution

The thermal analyses are performed for 1/3 FW (including manifold, grids and bottom plate) and 1/2 sub-module (including bottom plate). The analyses results show that the temperature distributions in different zones are in the permissible temperature range of different materials and acceptable. The temperature results are summarized in Table IV. Detailed temperature distributions are shown in Figure 5 and 6.

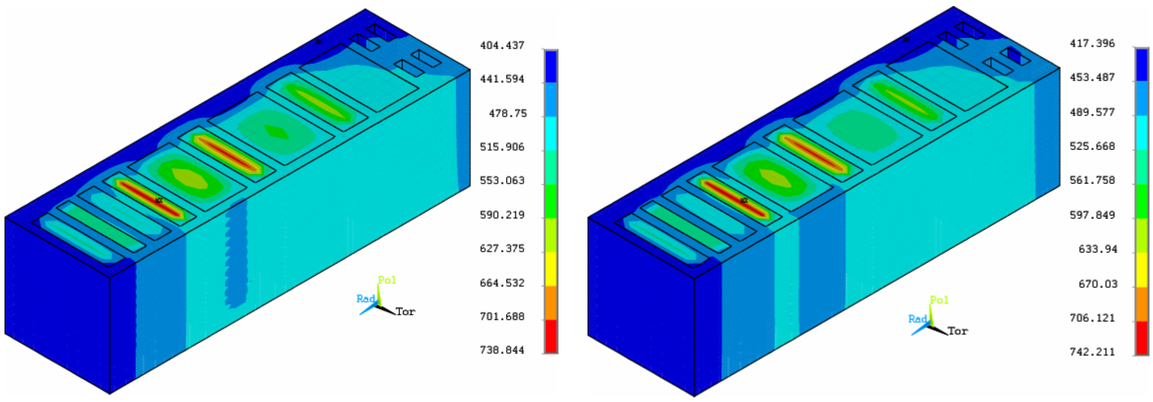
TABLE IV: SUMMARY OF TEMPERATURE IN DIFFERENT ZONES

Component	Zones	Max. Temperature (°C)	
		Normal condition	Extreme condition
FW	Be Armor	486	550
	Structure Material	513	537
Sub-module	Be Pebble Bed	611	613
	Li4SiO4 Pebble Bed	738	742
	Structure Material	524	526



normal condition *extreme condition*

FIG. 5. Temperature distribution of FW



normal condition *extreme condition*

FIG. 6. Temperature distribution of sub-module

3. Thermal Mechanical Analysis

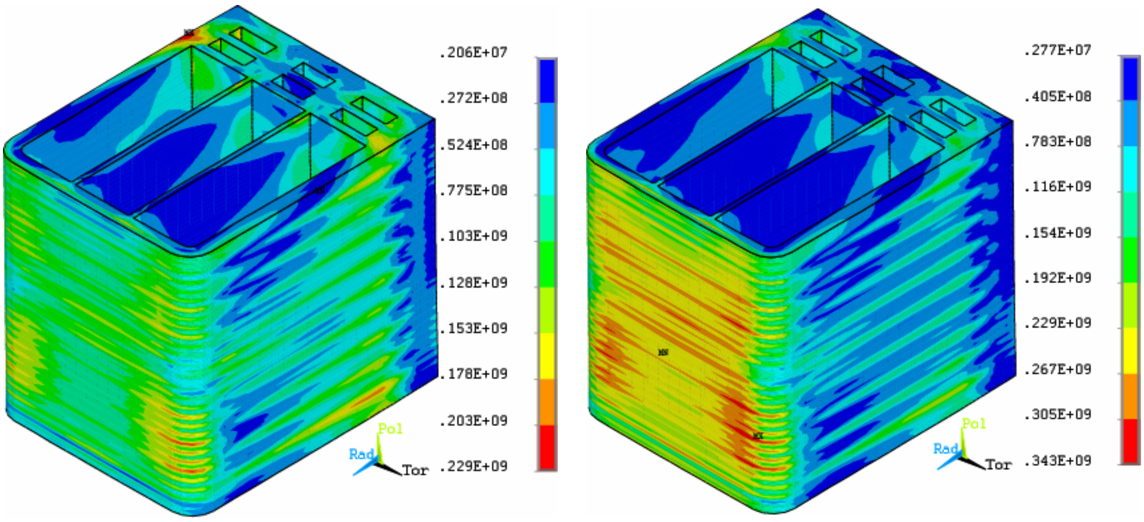
Preliminary structural analysis has been carried out on the basis of temperature distributions of the test module components (both in normal condition and extreme conditions for NT phase) using the ANSYS code. 1/3 FW segment (including 30 channels in series) and 1/2 sub-module are simulated using the elastic approach for the case of thermal loading (thermal stresses). The EM heat and stress will be considered together in the future. The irradiation and creep effects are not taken into account.

In the analyses, temperature distributions resulting from the thermal hydraulic analysis are applied. Helium pressure of 8 MPa inside the cooling tubes is considered.

The mechanical analyses performed for 1/3 FW and 1/2 sub-module show that the stress distributions in FW and sub-module are acceptable. The stress results are summarized in Table V. Detailed temperature distributions are shown in Figure 7 and 8.

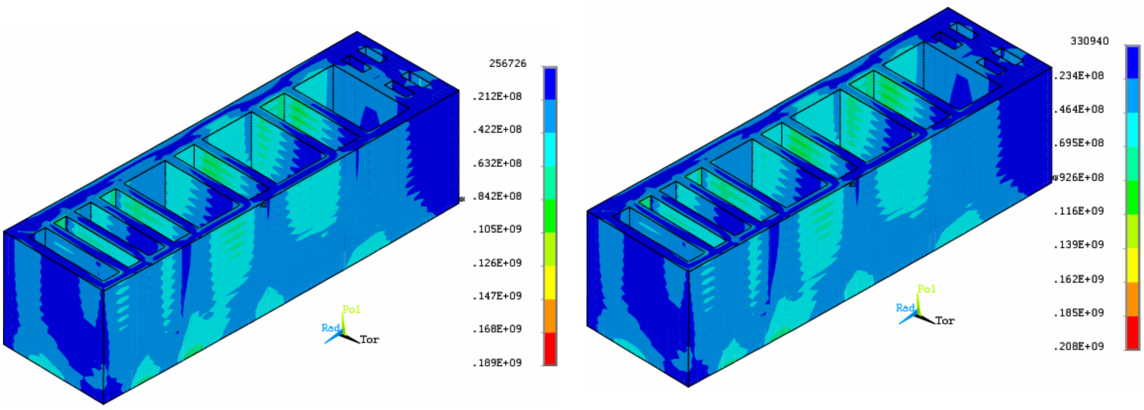
TABLE V: SUMMARY OF STRESS IN DIFFERENT COMPONENTS

Component	Maximum intensity stress [MPa]	
	Normal condition	Extreme condition
FW	229	343
Sub-module	189	208



normal condition *extreme condition*

FIG. 7. Stress intensity distribution of FW



normal condition *extreme condition*

FIG. 8. Stress intensity distribution of cooling plate in sub-module

The detailed analysis of the whole test module is still required. It is planned to calculate the transient stress in the test module in accordance with the operating scenario.

4. Conclusions

The static 3-D thermal and mechanical analysis has been performed for the CH HCSB TBM. The models used in the analysis are simplified reasonably.

The distributions of temperature in the FW segment and sub-module of the CH HCSB TBM have been given for the normal and extreme conditions for ITER NT phase. The analyses results show that the temperature distributions in different zones are in the permissible temperature range of used materials and acceptable.

The results of thermal mechanical analysis for FW segment and sub-module of the CH HCSB TBM show that the maximum value of stress intensity is below the breakdown limit 3Sm both in the normal and extreme conditions.

According to the above thermal hydraulic and mechanical analyses, it is confirmed that the design of the CH HCSB TBM is reasonable and is acceptable. It can be operated safely under the future ITER conditions.

References

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