Design and Technology Development of Solid Breeder Blanket Cooled by Supercritical Water in Japan

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Abstract. This paper presents results of conceptual design activities and supporting R&D's of a solid breeder blanket system for the demonstration of power generation fusion reactors (DEMO blanket), which is cooled by supercritical water. The Fusion Council of Japan developed the long-term research and development program of the blanket in 1999. Among the program, Japan Atomic Energy Research Institute has been assigned as a hub institute for developing a solid breeder blanket system in Japan. To make the fusion DEMO reactor more attractive, higher thermal efficiency of more than 40 % has strongly been envisaged. The design work has shown the feasibility of the first wall thermo-mechanical performance and tritium breeding performance of the blanket. In parallel with the design activities, engineering R&D's have extensively been conducted, which cover all necessary issues, such as, material development for structural materials, tritium breeding materials and neutron multiplier materials, neutronics experiments and analyses, and development of the fabrication technology of the blanket module.

1. Introduction

The Fusion Council of Japan has established the long-term research and development program of the blanket in 1999. In the program, Japan Atomic Energy Research Institute has been designated as a leading institute for developing a solid breeder blanket system in Japan. To make the DEMO reactor more attractive, higher thermal efficiency of more than 40 % has been strongly envisaged. From this viewpoint, the conceptual design of the DEMO reactor has been performed by JAERI recently, aiming at the achievement of similar plasma performance, such as fusion power, Q value, and neutron wall load with more economical attractiveness [1]. In line with the reactor design proposed, the DEMO blanket design has been intensively conducted. Major design parameters of the DEMO blanket are summarized in Table I. Load conditions and applied materials are similar to those of SSTR[2]. Therefore, past R&D results are available. Not only the design development, but also recent achievement of technology development was reported in this paper.

2. Design Development

One of most critical issues of the DEMO blanket design is the removal of a high heat flux of 1 MW/m^2 onto the first wall, while keeping the temperature of the first wall structure lower than 450 °C with exit coolant temperature, 510 °C. To solve this problem, a unique coolant flow pattern has been developed in this design. As can be seen in *FIG. 1*, the coolant with the inlet temperature, 280 °C first flows through the first wall area of the blanket modules, which are connected in series, and the coolant temperature is raised up to around

TABLE I: MAJOR DESIGN PARAMETERS OF SUPERCRITICAL WATER COOLED BLANKET

Item	Value
Surface heat flux	0.5 (peak 1) MW/m^2
Neutron wall load	3.5 (peak 5) MW/m^2
Neutron Fluence	>10 MWa/m^2
Coolant Material	Supercritical water
Coolant Pressure	25 MPa
Inlet / Exit Temperature	280 /510 °C
Tritium Breeding Ratio	>1.05
Structural Material	RAFS* (F82H) and/or ODS RAFS**
Tritium Breeder	Li_2O or Li_2TiO_3
Neutron Multiplier	Be or $Be_{12}Ti$

* Reduced activation ferritic steel
** Oxide Dispersion strengthened RAFS

380 °C at the exit of the first walls of the same series of modules. Then, the coolant flows into the breeding area of the blankets, which are also connected in series, and at the exit the coolant temperature of 510 °C can be obtained (FWs-to-Breeders Series Cooling Pattern). The thermal efficiency analysis of the cooling system showed that the thermal efficiency of more than 41 % is expected with this flow pattern by the heat balance calculation of the process flow diagram of the cooling system.

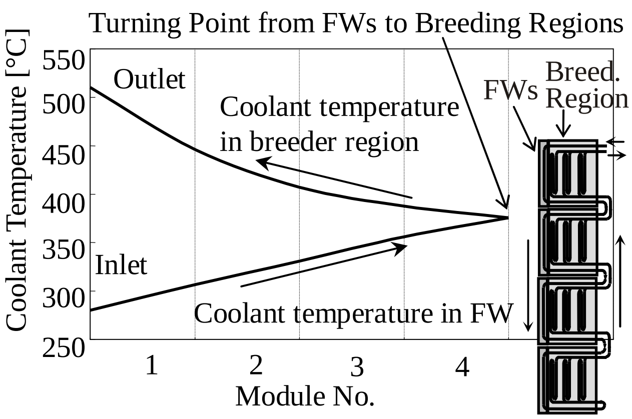

FIG. 1. Coolant Temperature Design by FWs-to-Breeders Series Cooling Pattern.

Detailed structure of the blanket module is shown in *FIG. 2*. Dimension of the blanket module is smaller than 2 m high, 2 m wide, and 0.6 m thick. Reduced activation ferritic steel, F82H (and/or ODS ferritic steel), which is currently under development by JAERI, was selected as the structural material. Ceramic breeder and beryllium neutron multiplier are packed in a form of a small pebble in a layer structure as shown in the figure. Lithium ceramics, such as Li_2TiO_3 or Li_2O, was selected as the primary candidate tritium breeder material. Beryllium or inter-metallic compound, such as $Be_{12}Ti$, was selected as the neutron multiplier.

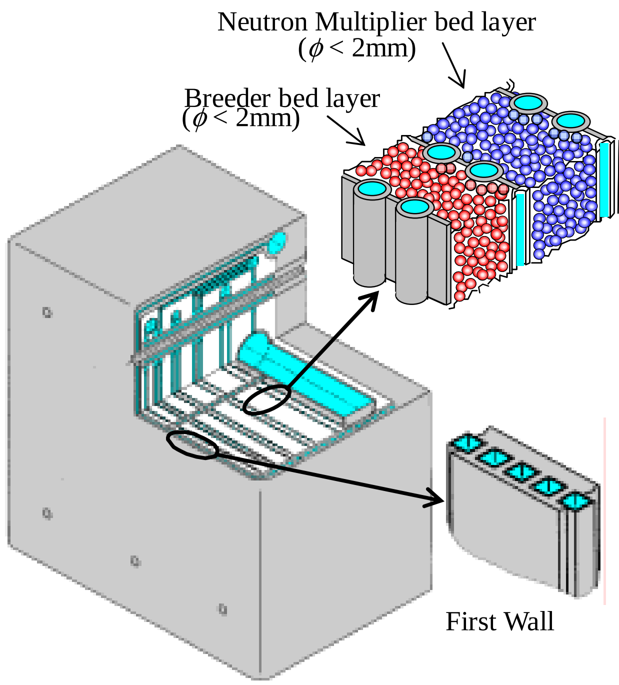

FIG. 2. Schematic structure of the supercritical water cooled blanket.

In the thermal and neutronics analyses of the breeding blanket, it is the most important point that the temperatures of the breeder and multiplier materials are required to be kept in the appropriate range without reducing the net tritium breeding ratio (TBR) less than 1.05, from the viewpoints of fuel self sufficiency and preparation of startup fuel for the next fusion plant. In this study, neutron and γ-ray spectrum analyses have been performed by using one dimensional S_N code, ANISN with the group constant set, FUSION-40.

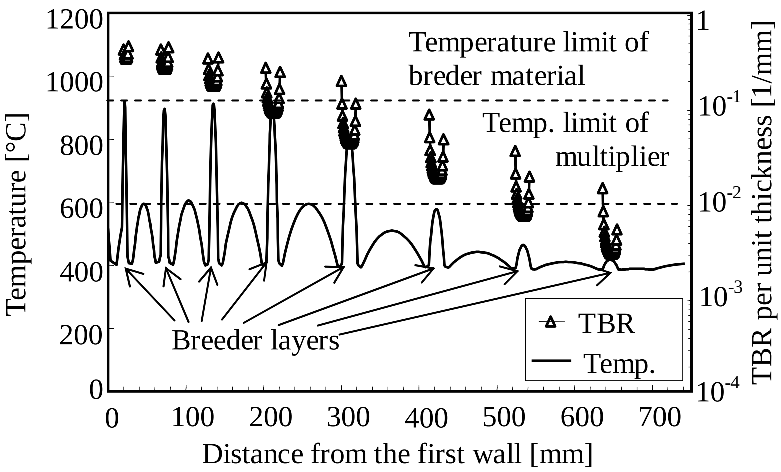

FIG. 3. Profiles of temperature and tritium breeding ratio along the thickness of the blanket.

TABLE II: RESULTS OF TBR CALCULATION WITH CANDIDATE OPTIONS OF MATERIALS AND STRUCTURE.

Materials	Li_2O / Be		Li_2TiO_3 / Be		Li_2TiO_3 / $Be_{12}Ti$				
^{6}Li Enrichment	30%	90%	30%	90%	90%	30%	90%	30%	90%
Packing Structure	Breeder / Multiplier Separate					Breeder + Multiplier Mix			
Temperature Limits	Breeder 900°C				900°C	600°C		900°C	
	Multiplier 600°C				900°C				
Local TBR	1.53	1.56	1.41	1.52	1.37	1.24	1.35	1.35	1.43
Coverage Requirement*	69%	67%	74%	69%	77%	85%	78%	78%	73%

* Required coverage fraction of the plasma facing surface of the breeding region of the blanket in the total area of the plasma facing surface, to achieve net TBR, 1.05.

Nuclear heating rate and TBR has been estimated by using APPLE-3 code. By using obtained values of nuclear heating rate, one dimensional thermal analysis has been performed to obtain temperature distribution [3]. *FIGURE 3* shows the distribution of local TBR in radial thickness direction, together with the temperature distribution in case where 30% ^{6}Li enriched Li_2TiO_3 and Be were applied as the breeder and multiplier materials. As can be seen from this figure, temperature of the breeder can be kept below the temperature limit of 900 °C. In this case, the local TBR reached 1.41, which satisfies the net TBR of 1.05 with 74% of coverage ratio of the blanket in the total plasma facing surface area in the vacuum vessel. Table II summarizes estimated values of TBR with major candidate options of materials, ^{6}Li enrichment and structure. Li_2TiO_3 and $Be_{12}Ti$ is expected to have better compatibility with water in high temperature than Li_2O and Be. Even in case Li_2TiO_3 or $Be_{12}Ti$ are applied, net TBR satisfied more than 1.05.

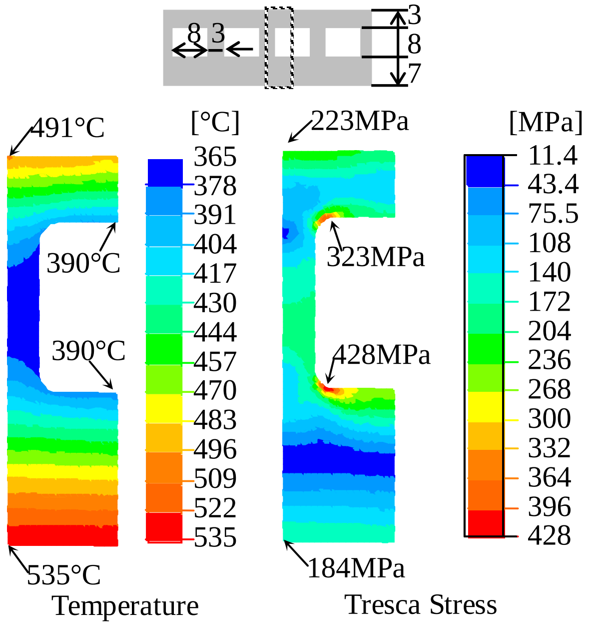

FIG. 4. Temperature and stress analyses of the first wall structure.

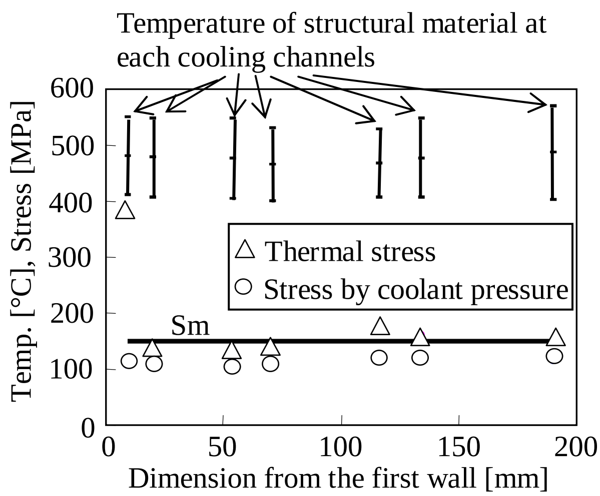

FIG. 5. Estimated values of temperature and stresses at each cooling channels.

In the design process, thermo-mechanical design is also another critical issue for the feasibility of the design. *FIGURE 4* shows the results of temperature and stress analyses of the first wall structure by using ABAQUS code based on the heating and cooling conditions specified by the design requirement and coolant temperature design. The highest temperature appears at the rear side of the first wall due to the apparent heat flux (about 0.4 MW/m^2) by the volumetric heating in the breeder zone. Peak stress appeared at the corner of the cooling channel, however, it satisfies the 3Sm value of the reduced activation ferritic steel, F82H, at 500 °C (430 MPa). *FIGURE 5* shows the estimated values of the temperature and stress of structural material in this design. As can be seen from *FIG. 5*, the stress by the internal coolant pressure in the cooling channels and pipes satisfied Sm or 1.5Sm value. Temperature estimation showed the temperature ranges from 400 °C to 570 °C. This result indicates the necessity of the incorporation of creep effect in the thermo-mechanical design.

The design work included the analyses of tritium inventory and permeation, diverter design, power plant design, tritium systems for purge gas tritium recovery and water detritiation, the design of the remote maintenance system and blanket replacement procedure. Preliminary integration of the design of a solid breeder blanket cooled by supercritical water was achieved in this study.

3. Supporting Technology R&D’s

In parallel with the design activities, supporting technology R&D's have been extensively conducted, which cover development for structural materials [4], tritium breeding materials and neutron multiplier materials [5], neutronics performance experiments and analyses [6], evaluations of thermal characteristics of packed pebble bed [7] and development of the fabrication technology of the blanket module. Since the first wall with embedded cooling channels consists of rectangular cooling channels and flat panels, a hot isostatic pressing (HIP) technique has been applied for the first wall. A HIP-bonded F82H first wall mock-up with built-in rectangular cooling channels has been successfully fabricated, and tested to demonstrate the structural soundness under the accelerated heat flux condition of 2.7 MW/m^2. As can be seen from *FIG. 6*, it is confirmed that no degradation of the fatigue lifetime performance can be found in F82H after the HIP-bonding process [8].

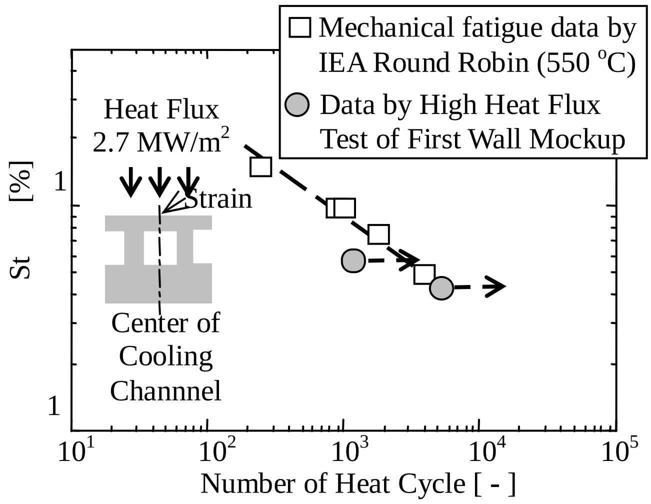

FIG. 6. Thermal fatigue durability of the first wall mockup under high heat flux test.

For the thermal design of the breeder layer, effective thermal conductivity of a pebble bed is the most important characteristics. By using the representative pebble of Li_2TiO_3 fabricated by Sol-Gel method [5], the measurement has been performed by single packing pebble bed and binary packing pebble bed. *FIGURE 7* shows the schematic structure of the measurement apparatus by hot wire method [7]. The test section simply consists of the sample pebble bed and the hot wire (PtRh heater) at the center in the axial direction. Effective thermal conductivity is calculated by observed transient temperature change of the hot wire. *FIGURE 8* shows the measured values of effective thermal conductivities of Li_2TiO_3 pebble beds. By applying

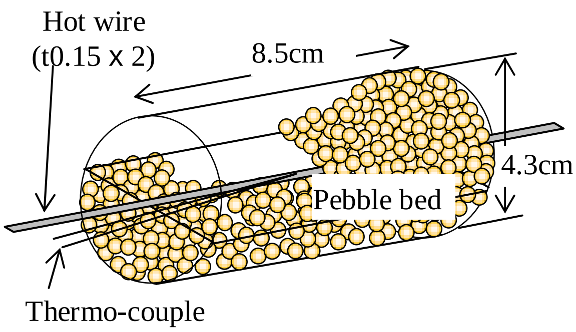

FIG. 7. Schematic structure of pebble bed thermal conductivity measurement apparatus by hot wire method.

binary packing of 1.91 mm diameter pebbles and 0.28 mm diameter pebbles, the effective thermal conductivity became 10 to 20 % larger than single packing pebble bed, which met with the correlation estimation. By this result, the uncertainty of the thermal design of the breeder pebble bed was decreased. Also, the hot wire method was extended to measure the effect of the stress in the pebble bed to the effective thermal conductivity, which is the most important unknown data of the thermo-mechanical design of the pebble bed blankets[9,10].

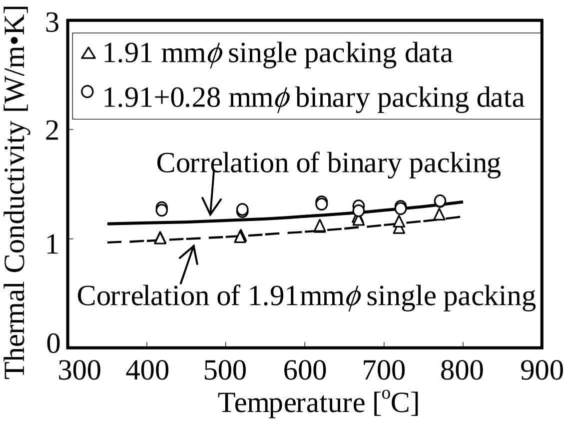

FIG. 8. Measured effective thermal conductivities of single and binary packed beds of Li_2TiO_3 pebbles.

4. Conclusions

(1) A supercritical water cooled solid breeder blanket was proposed as the advanced concept of the water cooled solid breeder blanket.
(2) Design development covered major critical issues. Preliminary integration of the design was achieved.
(3) Technology R&D’s progressed in the area of the first wall, box and pebble bed structure fabrication. The results of R&D’s were reflected to the blanket module design.

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