Comparison of Coolant Conditions in the Blanket for a Water-Cooled DEMO Reactor SlimCS*)

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(Received 7 December 2010 / Accepted 27 April 2011)

The blanket structure of the SlimCS has been studied under coolant condition of Pressurized Water Reactor (PWR) to improve the compatibility with F82 H. The neutronic and thermal calculation are performed for the simplified blanket structure, which Li_4SiO_4 pebbles or Li_2O pebbles for tritium breeding and $Be_{12}Ti$ pebbles for neutron multiplication are mixed and these pebbles are filled in the blanket. As a result, the TBR of blanket by PWR water condition is higher than those of sub-critical water condition because the tritium breeding area in the blanket is extended by decreasing thickness of coolant tube in comparison with sub-critical water condition. The blanket with PWR water condition can attain target of the net TBR (≥ 1.05) and satisfy condition of conducting shell for MHD stability.

Keywords: mixed pebble beds blanket, DEMO, SlimCS, neutronics, thermal analysis, PWR water condition

DOI: 10.1585/pfr.6.2405108

1. Introduction

Conceptual design of tritium-breeding blanket for SlimCS has been studied. The proposed blanket concept is that Li_4SiO_4 or Li_2O pebbles for the tritium breeding and $Be_{12}Ti$ pebbles for the neutron multiplication are mixed and these pebbles are filled in the blanket. The coolant condition was selected to be sub-critical water, whose temperature difference between inlet and outlet were 290°C and 360°C, respectively, and pressure was 23 MPa. The coolant flows in the toroidal direction as shown in Fig. 1. When Li_2O pebbles were mixed with $Be_{12}Ti$ pebbles, TBR was higher than 1.05 for the blanket with the thickness of 50 cm [1]. However, the compatibility of the blanket structural material (F82H) with the sub-critical water is a concern. As the second step, therefore, we replace the condition by the Pressurized Water Reactor (PWR) water condition of 15 MPa and 290-330°C to improve the compatibility with F82H. In addition, the PWR water condition has an advantage that matured technologies in nuclear power plants will be likely to reduce development risks in fusion plant engineering. In this paper, the comparison of PWR and sub-critical water conditions has been studied by numerical simulation.

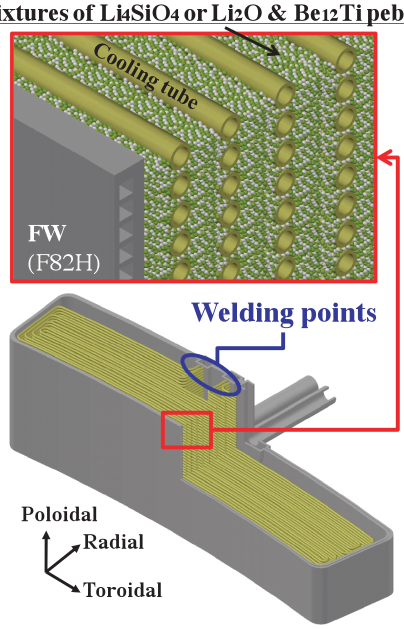

Fig. 1 Interior design of blanket by sub-critical water condition.

2. Cooling with PWR Water Condition

From the viewpoint of the effective cooling of the first wall and blanket, the inlet temperature of coolant is desired to be as low as possible. The water coolant with low temperature, however, may erode the structural material due to the residual hydrogen peroxide produced (H_2O_2) by radiolysis water decomposition. H_2O_2 starts to pyrolytically decompose at 240°C. Therefore, the inlet temperature of the first wall coolant is selected to be 290°C with the design of the coolant plumbing. On the other hand, use of the PWR water to the blanket requires a reduction of coolant plumbing length because of a reduced temperature range. The di-

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*) This article is based on the presentation at the 20th International Toki Conference (ITC20).

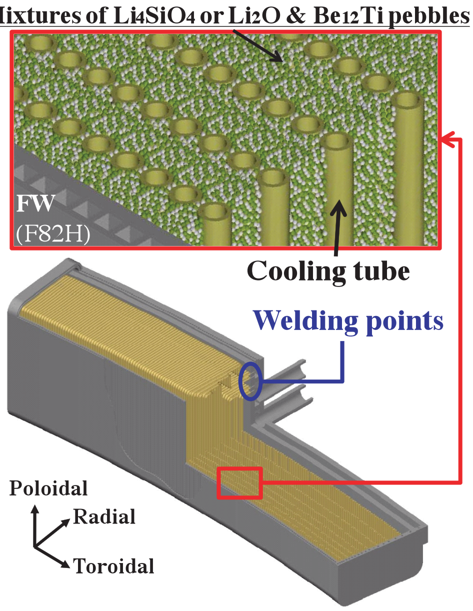

Fig. 2 Interior design of blanket by PWR coolant condition.

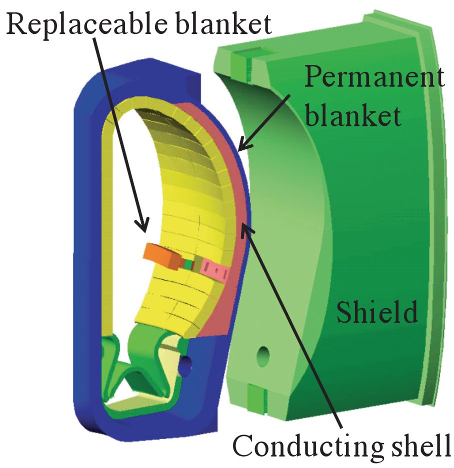

Fig. 3 Blanket sectors for SlimCS.

rection of coolant plumbing in the blanket is changed from toroidal to poloidal direction as this solution for the problem. As a result, all length of coolant plumbing can be decreased without changing the configuration of the blanket module as shown in Fig. 2. This design has a possibility of increasing TBR due to a relative increase the fraction of breeding materials by decreasing thickness of coolant tube.

3. Simplification of Blanket Structure for SlimCS

In the DEMO reactor, a displacement per atom (dpa) reaches about 100 dpa/year at the first wall in blanket. The existence of welding points deteriorates strength of coolant tube. Therefore, the blanket without welding points minimizes the risk of irradiation damage of welding lines. In previous study, the simplified blanket structure for SlimCS DEMO reactor was proposed from viewpoint of engineering feasibility [1]. The major parameters for SlimCS are a plasma major radius of 5.5 m, an aspect ratio of 2.6 and fusion power of 2.95 GW, respectively [2]. Figure 3 shows the blanket sector for SlimCS. The blanket for SlimCS consists of the replaceable and permanent blanket. The permanent blanket is high temperature shielding for reduce the neutrons. The conducting shell for plasma positional stability and high beta access is installed in between replaceable and permanent blanket.

The thickness of conducting shell of F82H is 0.07 m in the radial direction. The replaceable blanket modules of SlimCS are segmented into toroidally-long modules with the size of 1.4-2 m (toroidal) × 0.5-0.6 m (poloidal) for suppression of the electromagnetic force [2]. The thickness of replaceable blanket should be designed to be as thin as possible since it is important for high plasma performance to locate the conducting shell close to plasma as possible. The conducting shell needs to be located at $r_w/a_p \leq 1.35$ for plasma positional stability and high beta access. Here a_p is plasma minor radius, and r_w is distance between the center of the plasma and the center of conducting shell. In the case of SlimCS with $a_p = 2.1$ m, the thickness of blanket should be 0.5 m or less to meet $r_w/a_p \leq 1.35$, when the gap between the separatrix and the first wall is 0.15 m. The design target of this study is to satisfy the net TBR ≥ 1.05 using the blanket with the thickness of 0.5 m or less.

4. Calculation Conditions

The sizes and arrangement of the cooling tubes for the proposed blanket were changed in accordance with the neutron wall load (NWL). Actually, the blanket was approximated by a slab model for the calculations as shown in Fig. 4. The cooling tubes were replaced with slabs having the equivalent cross section. In the 1-D calculations of the neutronic and thermal analysis for the blanket system, the ANIHEAT code with the nuclear data library FENDL-2.0 [3] was used.

The neutronic performances were calculated on local TBR and nuclear heating in the blanket. The temperature of blanket was evaluated by the 1-D thermal conduction equation. The thickness of each layer was determined to satisfy the operation temperature of materials. The local TBR was evaluated by changing NWL 1 to 5 MW/m^2 and heat load was fixed at 0.5 MW/m^2. The mixed pebble beds conditions were ^{6}Li enrichment of 90% and a packing fraction of 80%. The fraction of breeder (Li_4SiO_4 or Li_2O), $Be_{12}Ti$ and He-gas were 12%, 68% and 20%, respectively. The effective thermal conductivity of the mixed pebbles is defined by the combination of the conductivities of breeder and multiplier pebble beds [4–6] in accordance with the fraction as shown in Fig. 5. The coolant flows in the poloidal direction. The coolant was assumed to be PWR water conditions of 15 MPa and ΔT = 40°C (290-

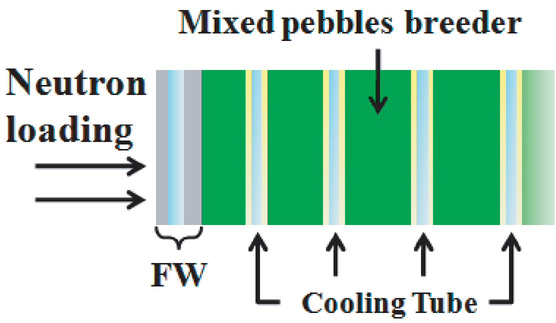

Fig. 4 1-D model for mixed pebbles breeder blanket.

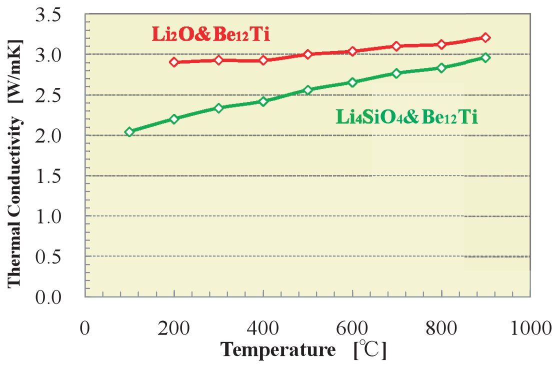

Fig. 5 Thermal conductivities of breeder and multiplier.

330°C). The upper coolant velocity was limited to 6 m/s and the outlet temperature was less than 330°C. The operation temperature of Li_4SiO_4, Li_2O, $Be_{12}Ti$ and F82H was limited to 900°C, 700°C, 900°C and 550°C, respectively.

5. Result of Calculations

5.1 Dependence of local TBR on neutron wall load

The local TBR was evaluated by changing NWL from 1 to 5 MW/m^2 as shown in Fig. 6. In Fig. 6, the thickness of blanket was fixed at 0.6 m. In Fig. 6, in all cases, the tendency of local TBR are similar. With decreaseing the NWL from 5 to 1 MW/m^2, the local TBR is improved because of a reduction of the coolant area in the blanket. The local TBR of blanket by PWR water condition is higher than those of sub-critical water condition because the tritium breeding area in the blanket is extended by decreasing thickness of coolant tube in comparison with sub-critical water condition. Moreover, there is an advantage that the TBR increase because of rising the Be $(n, 2n)$ reactivity as a result for the reduction of the coolant tube in thickness.

5.2 Evaluation of net TBR

The NWL is changed along the poloidal direction. Taking account in the distribution of the neutron wall load, the suitable designs of the blanket module needs to be accurate in neutronics for net TBR. Therefore, the layout of suitable blanket designs along the poloidal direction was

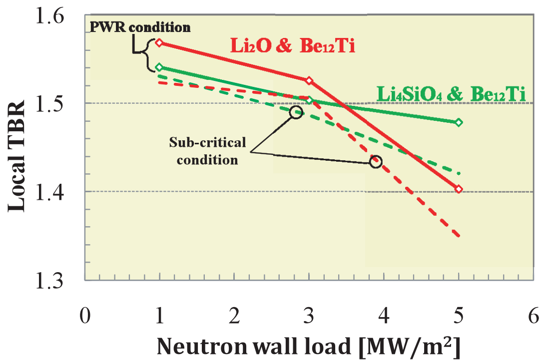

Fig. 6 Dependence of local TBR on neutron wall load.

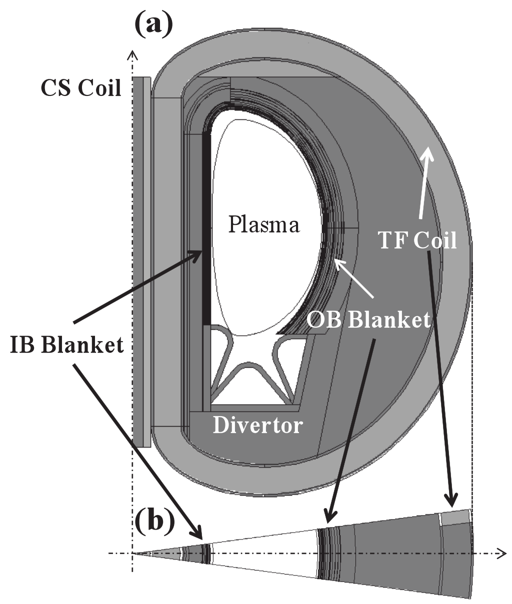

Fig. 7 MCNP calculation model for SlimCS (a: vertical cross section in the 3-D model and b: horizontal cross section at mid-plane).

calculated by the 3-D Monte Carlo N-Particle transport code MCNP-5 [7] with the nuclear data library ENDF/B-VII [8]. Figure 7 shows the 3-D MCNP calculation model for SlimCS. The model includes the geometrical arrangement of the inboard (IB) and outboard (OB) blanket, the divertor, the central solenoid (CS) and toroidal field (TF) coils. By assuming toroidal axisymmetry, 1/24 sector of the reactor was modeled with reflecting boundaries. The surface area of IB blanket, OB blanket and divertor were 179 m^2, 489 m^2 and 326 m^2, respectively. The neutron volume source for plasma emitted neutron with the energy of 14.06 MeV. The blanket coverage loss by the divertor is 11.8% and loss by the ports is 1%. In addition, rims, ribs and gap of the structure in the blanket coverage are 7.3%, 3% and 1%, respectively. Therefore, the total coverage of blanket is 75.9%.

Figure 8 shows the poloidal distribution of the NWL. The peak NWL in the IB and OB blanket were 2.93 and

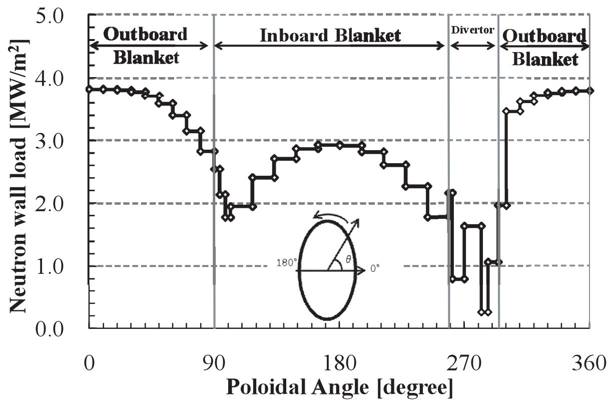

Fig. 8 Distribution of neutron wall load for SlimCS.

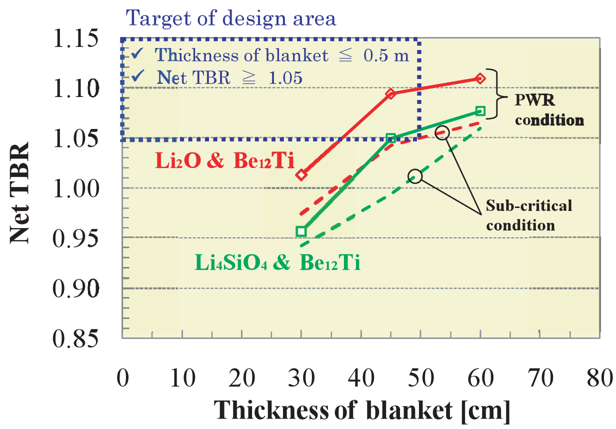

Fig. 9 Dependence of net TBR on blanket in thickness.

3.82 MW/m^2, respectively. The average NWL in the IB and OB blanket were 2.44 and 3.50 MW/m^2, respectively. As a result, this concept has a possibility of increasing TBR due to a relative increase the fraction of breeding materials, because of a reduction of coolant area in blanket.

Figure 9 shows a blanket thickness dependence of the net TBR. The net TBR was calculated by considering the poloidal distribution of NWL in Fig. 8 and the dependence of local TBR on the NWL in Fig. 6. In Fig. 9, the thickness of the OB blanket was changed from 0.3 to 0.6 m and the thickness of the IB blanket was fixed at 0.3 m. The figure 9 shows that the net TBR of Li_2O&$Be_{12}Ti$ was higher than those of the other cases. The reason why Li_2O&$Be_{12}Ti$ shows grater TBR than Li_4SiO_4&$Be_{12}Ti$ was that Li_2O&$Be_{12}Ti$ was different from Li_4SiO_4&$Be_{12}Ti$ in having the high content of ^6Li. The Li_2O&$Be_{12}Ti$ and Li_4SiO_4&$Be_{12}Ti$ attained the target of the net TBR (≥ 1.05) at the blanket thickness of 0.35 m and 0.45, and the Li_2O&$Be_{12}Ti$ and Li_4SiO_4&$Be_{12}Ti$ can keep location for conducting shell ($r_w/a_p \leq 1.35$).

6. Conclusions

The blanket structure of the SlimCS has been studied under coolant condition of PWR to improve the compatibility with F82H. Use of the PWR water to the blanket requires a reduction of coolant plumbing length because of a reduced temperature range. The direction of coolant plumbing in the blanket was changed from toroidal to poloidal direction. The neutronic and thermal calculation were performed for the simplified blanket structure, which Li_4SiO_4 pebbles or Li_2O pebbles for tritium breeding and $Be_{12}Ti$ pebbles for neutron multiplication were mixed and these pebbles were filled in the blanket. As a result, the TBR of blanket by PWR water condition was higher than those of sub-critical water condition because the tritium breeding area in the blanket was extended by decreasing thickness of coolant tube in comparison with sub-critical water condition. Li_2O&$Be_{12}Ti$ and Li_4SiO_4&$Be_{12}Ti$ could attain target of the net TBR (≥ 1.05) and satisfy condition of conducting shell position ($r_w/a_p \leq 1.35$) for MHD stability. Hence, the mixed pebble bed blanket is preferable for SlimCS DEMO reactor. When the using Li_2O as tritium breeder would turn out to be difficult from the viewpoint of material health, the Li_4SiO_4&$Be_{12}Ti$ blanket is main option for SlimCS.

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