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Water-Cooled Solid Breeding Blanket for DEMO

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For tokamak fusion DEMO, neutronics and thermal design was carried out to find a blanket concept with reality. For the continuity with the Japanese ITER-TBM options, this study considered water-cooled blanket with solid breeding materials of Li ceramics (Li_4SiO_4, Li_2TiO_3 and Li_2ZrO_3) and Be multipliers (Be and $Be_{12}Ti$). On the based on multilayered structure with Li_4SiO_4 pebbles, Be plate and mixture of $Li_4SiO_4/Be_{12}Ti$, the local TBR of 1.42 (corresponds to the net TBR of 1.05) was obtained. In addition, it was concluded that in-between conducting shell structure can be placed at r_w/a = 1.32-1.35 with satisfying fuel self-sufficiency.

Keywords: blanket, tritium breeding ratio, solid breeder, DEMO, fusion reactor

1. Introduction

Blanket of fusion reactor must meet three major requirements, 1) tritium self-sufficiency, 2) removal of nuclear heating, and 3) structural strength against electromagnetic forces acting on disruptions. The common maneuver in blanket design is to minimize the areas of coolant and structural materials so as to ensure fuel (tritium) self-sufficiency. Generally, it is difficult to ensure fuel self-sufficiency in itself. It is even more difficult to find a consistent solution satisfying all these requirements. Water-cooled solid breeding blanket treated in this paper, is regarded as a conservative and less challenging blanket concept. However, the fact is that the concept still has difficult problems to be resolved. In this paper, we report the blanket design study for a compact low aspect ratio DEMO "SlimCS" and clarify the critical design issues.

2. Basic concept of blanket

The DEMO reactor, SlimCS, has a major radius of 5.5 m, aspect ratio (A) of 2.6, maximum field of 16.4 T, normalized beta (β_N) of 4.3 and fusion output of 2.95 GW [1]. The average neutron wall load is 3 MW/m^2. The reactor is characterized by a reduced-size central solenoid (CS) whose main function is plasma shaping rather than plasma current ramp-up. The CS has an outer radius of 0.7 m, being capable of moderate plasma shaping (triangularity of ~0.35) and plasma current ramp of 3.8 MA. Although such a CS provides a constraint in tokamak operation, especially in the current ramp-up phase, it has advantages to allow us to introduce a thin toroidal coil system, decreasing the reactor weight and perhaps contributing a reduction of the construction cost. In addition, the reduced-size CS produces the possibility of low A, which leads to advantages in physics design such as high elongation of plasma, high plasma current, high Greenwald density limit and high beta limit.

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The DEMO blanket is required to consider continuity with the Japanese ITER-TBM program [2] in which water-cooled solid breeder blanket using lithium ceramics (breeder), Be or $Be_{12}Ti$ (neutron multiplier) and F82H [3] (structural material) will be developed. In addition, a conducting shell structure should be installed near the plasma (preferablly, r_w/a ~ 1.3) on the outboard side. For this purpose, the blanket consists of replaceable and permanent blanket, and the front and side plates of the permanent blanket are 0.07 m in thickness so that the plates have the function of the conducting shell (called "Kameari shell") [4] assembly, as indicated in Fig.1. Since the first wall area on the outboard side is wide in a low-A reactor like SlimCS (inboard 27%, outboard 73%), the demand for tritium breeding on the high field side is comparatively reduced. This leads to the breeding blanket concept consisting of small inboard blanket and large outboard blanket modules. For this reason, SlimCS is designed to have replaceable and permanent blankets on the outboard side while no permanent blanket is installed on the inboard side.

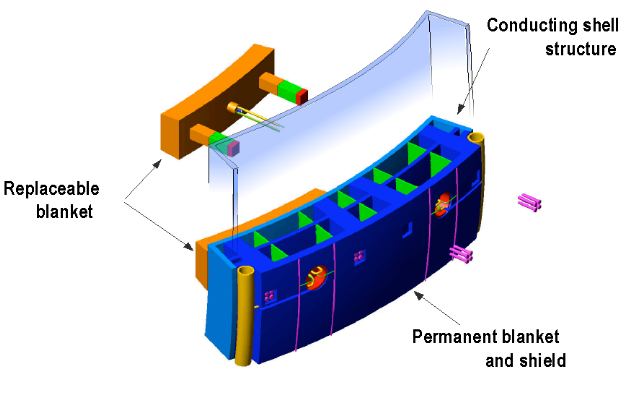

Fig.1 Replaceable and permanent blanket concept of SlimCS.

The temperature range and pressure of the coolant is one of the key design issues. The coolant temperature is required to be about 300ºC at least so as to avoid corrosion by radiation-produced hydrogen peroxides and radiation embrittlement like light water reactors. However, use in the PWR conditions (15 MPa, 285-325ºC) will be problematic in that the required large amount of coolant in the blanket can detract the self-sufficiency of tritium production. On the other hand, use of supercritical water (25 MPa, 280-510ºC), which can allow heat removal with a smaller amount of water because of wide operating temperature range, is expected to lead serious corrosion of F82H. Accordingly, we decided to use water in the subcritical water condition of ~23 MPa and 290-360ºC (ΔT = 70K).

3. Blanket Structure

3.1. Blanket segmentation

A challenging issue in the blanket design is to assure robustness of the blanket casing and its support against disruptions. This requirement is a difficult issue especially for the replaceable blanket. Because it must not only withstand enormous electromagnetic (EM) forces acting on disruptions, but be easily de-installable and installable for periodic replacement. From the point of view of structural robustness, smaller blanket casing is desirable while such a casing seems to be problematic regarding tritium breeding. After all, the blanket casing should be large as long as it withstands disruptions.

In order to determine a reasonable blanket casing in terms of the EM forces, eddy current due to a disruption and the resulting EM force moments were estimated. On the basis of the analysis on various blanket casings for a disruption (plasma current quench time of 0.03 s, without suffering vertical displacement event), we come to a conclusion that toroidally-long blanket casing has advantage in the viewpoint of support against disruptions [5] when the blanket is fixed with supports in the toroidal direction (Fig.1).

3.2. Neutronics and thermal design of blanket

The purpose of this research is to find a promising candidate of blanket concept. In this early stage of research, the one-dimensional analysis with simplified models is efficient to flexibly deal with a try and error process in the design. The code used in this study is an ANIHEAT code that calculates the nuclear heating distribution and solves heat transfer in the blanket. Eventually, the code provides the temperature profile in the blanket and the local tritium breeding ratio (TBR). The required local TBR for SlimCS is estimated to be ≥ 1.38 to reach the net TBR of ≥ 1.05.

Based on the result of various model calculations, the blanket is designed to have multilayered structure as shown in Fig.2. This is because such structure installing breeder and multiplier zones alternately can provides the highest TBR. Compared with other lithium ceramics such as Li_2TiO_3 and Li_2ZrO_3, Li_4SiO_4 has high Li density per unit volume (Table 1) and Si has low cross section for inelastic collisions in MeV range (Fig.3). This suggests that Li_4SiO_4 is anticipated to have the highest TBR among them. Actually, the calculated TBR is as expected. A distinctive feature of the blanket interior is to use both Be plate and $Be_{12}Ti$ pebbles in accordance with the intension. From the point of view of chemical stability, $Be_{12}Ti$ is favorable as neutron multiplier. However, we determined not to use $Be_{12}Ti$ in the forward multiplier zones (in the first and second multiplier zones). This is to avoid neutron absorption in MeV range by Ti of $Be_{12}Ti$. Be intrinsically has excellent thermal conductivity (nominally, 200 W/mK). When it used as pebbles, however, the conductivity decreases to as low as 7 W/mK [6], which will make the thermal design of Be layers. For this reason, Be plates are allocated in the forward multiplier zones. Incidentally, Be plates are canned to avoid the reactive decomposition of Li_4SiO_4 by Be. In the backward multiplier zones of the blanket, neutron absorption by Ti of $Be_{12}Ti$ becomes less important because of reduced energy of neutrons. In fact, there is an affirmative reason for using $Be_{12}Ti$ in the backward. This is because $Be_{12}Ti$ is allowed to use in the mixture of Li_4SiO_4 without any partition due to its chemical stability, which contribute to increasing TBR.

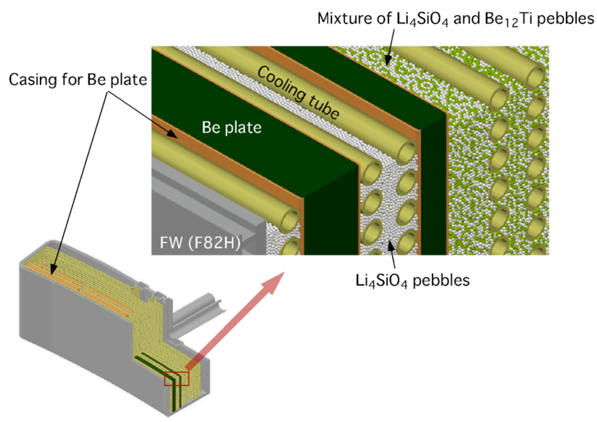

Fig.2 Interior of replaceable blanket

The blanket structure shown in Fig.2 is modeled one-dimensionally and the nuclear heating and the temperature in the steady state are calculated. Figure 4 is an optimized arrangement in which the thickness of each material is determined to satisfy the operating temperature; ≤ 900ºC for Li_4SiO_4 and $Be_{12}Ti$, and 600ºC for Be. The coolant temperature is assumed to be same as the outlet temperature (360ºC) and the neutron wall load is 5 MW/m^2 which corresponds to the peak wall load in the reactor when the average neutron wall load is 3 MW/m^2. Notice that the nuclear heating of Li_4SiO_4 in the first and second breeder zones is as high as 100 W/cm^3. Since the heat thermal conductivity of Li_4SiO_4 pebbles is low (about 1 W/mK [7]), the zones must be as thin as 1 cm to meet the operating temperature.

Table 1 Comparison of lithium ceramics

	Li_4SiO_4	Li_2TiO_3	Li_2ZrO_3
Li density (g/cm^3)	0.51	0.43	0.38
Thermal conductivity (W/mK)	2.4	1.8	0.75
Swelling ΔV/V (%)	1.15	0.8	0.5
Reactivity with H_2O	small	none	none

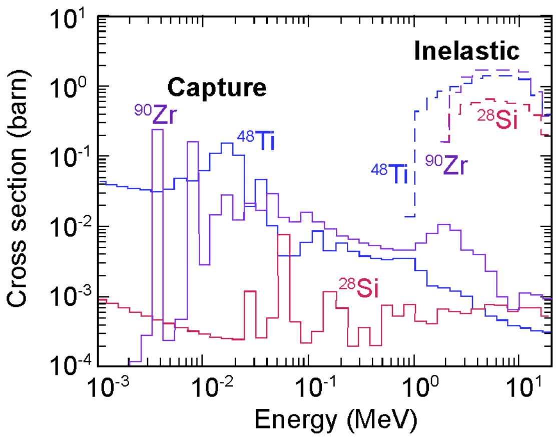

Fig.3 Cross section for neutron capture and inelastic collision for metals of Li ceramics.

The calculated local TBR is summarized in Table 2, indicating that the required local TBR (≥ 1.38) is satisfied for both cases with Li_4SiO_4 and Li_2TiO_3 pebbles. In addition, most of tritium is produced on the outboard side. The thickness of the replaceable and permanent is about 40 cm and 30 cm, respectively. Despite the thickness, the permanent blanket contributes little to the TBR. Figure 5 illustrates the distribution of the local TBR at each breeder stage (zone) for the Li_4SiO_4 case. The figure suggests that the importance of the design for the replaceable blanket, especially for the forward breeder stages of the blanket.

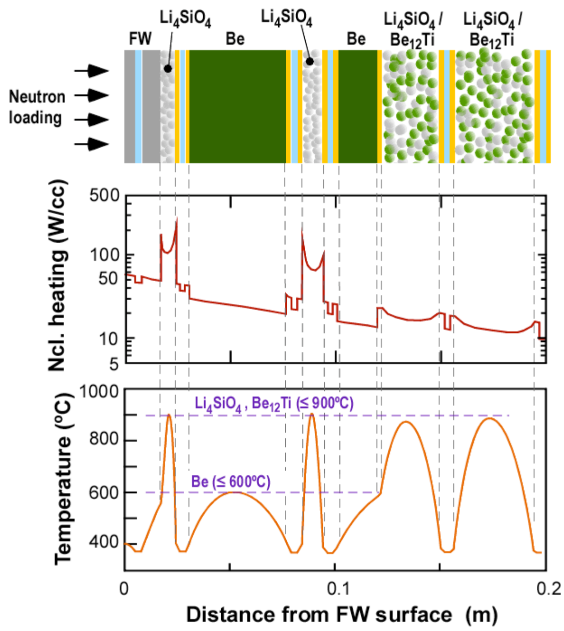

Fig.4 One-dimensional model of blanket and the calculated nuclear heating and temperature distribution.

Table 2 Local TBR for Li_4SiO_4 and Li_2TiO_3 pebbles

		Li_4SiO_4	Li_2TiO_3
Inboard	Replaceable blanket	0.31	0.30
Outboard	Replaceable blanket	1.07	1.04
	Permanent blanket	0.04	0.04
Total		1.42	1.38

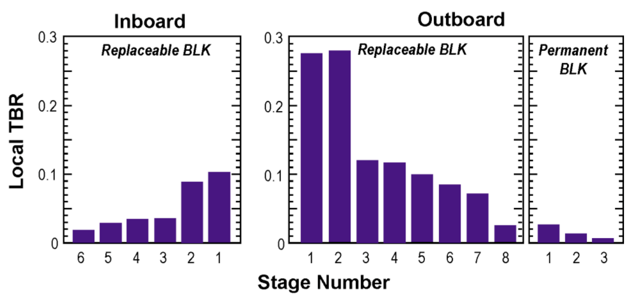

Fig.5 Local TBR produced in each breeder zone in the blanket using Li_4SiO_4 pebbles.

3.3. Conducting wall position and TBR

In SlimCS, the problem on the conducting wall position is equivalent to the problem on the segmentation of replaceable and permanent blankets. This is because the front plate of the permanent blanket plays a role of a conducting wall as shown in Fig.1. From the point of view of plasma design, the wall position should be close to the plasma as possible for high β_N access and vertical stability of plasma. On the other hand, the conducting shell attenuates neutron flux, leading to a reduction in TBR. As the calculated TBR of the present blanket options is near the verge of fuel self-sufficiency, the relation between the conducting shell position and TBR becomes a critical issue regarding blanket design. Since fuel self-sufficiency is a necessary requirement of fusion reactor, one might have to accept a setback of wall position to ensure fuel self-sufficiency even if the design value of β_N decreases.

Figure 6 shows the summation of the local TBR between the inboard blanket and the n-th breeder stage (zone) of the replaceable blanket. When the conducting shell structure is located just behind the breeder stage (this means the replaceable blanket has n stages of breeder), the local TBR in the breeding zones behind the wall is expected to be as low as 0.05. Therefore, in order to meet fuel self-sufficiency, the summation of the local TBR must be 1.33 (= 1.38-0.05) or higher. The figure indicates that this condition is satisfied when the number of breeder stages is seven or more. This indicates a necessity to arrange the conducting shell at r_w/a = 1.32 – 1.35, which may impose compromise on the design value of β_N.

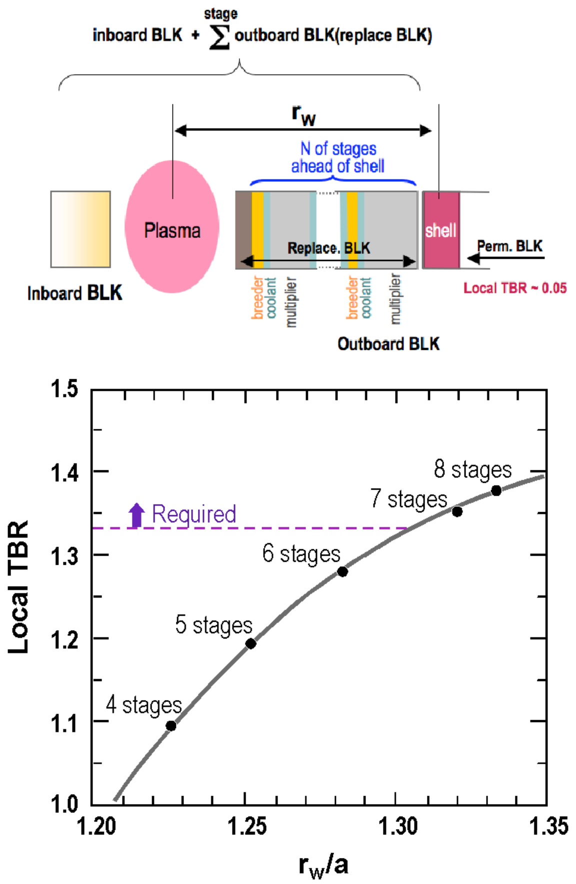

Fig.6 Relation between r_W/a and the number of breeder stages of the replaceable blanket on the outboard.

4. Summary

The present study focused on the neutronics and thermal design of water-cooled solid breeding blanket on SlimCS. Findings of this study are:

1) In the modeled calculation, a blanket concept satisfying fuel self-sufficiency can be envisaged using the presently available data.
2) In-between conducting shell structure can be placed at r_w/a = 1.32-1.35 with satisfying fuel self-sufficiency.

However, it must be noted that the present model calculation includes uncertainty in the treatment of contact heat resistance. This kind of heat transfer can be said to be an intrinsic difficulty in the design of solid breeding blanket. In order to pursuit reality of blanket design, it is necessary to find a concept that reduces uncertainty of contact heat resistance. For example, inserting a thin Be pebble layer between the Be plate and the casing improves the situation although it has a demerit in heat conductivity. In addition, more information on irradiation effect on heat conductivity of breeder and multiplier is required for reliable design.

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