Plasma and Fusion Research: Regular Articles Volume 6, 2405053 (2011)

Blanket Concept of Water-Cooled Lithium Lead with Beryllium for the SlimCS Fusion DEMO Reactor[*)]

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(Received 7 December 2010 / Accepted 25 March 2011)

As an advanced option for SlimCS blanket, conceptual design study of water-cooled lithium lead (WCLL) blanket was performed. In SlimCS, the net tritium breeding ratio (TBR) supplied from WCLL blanket was not enough because the thickness of blanket in SlimCS was limited to about 0.5 m so as to allocate the conducting shell position near the plasma for high beta access and vertical stability of plasma. Therefore, the beryllium (Be) pebble bed was adopted as additional multiplier to reach a required TBR (≥ 1.05). Considering the operating temperature of blanket materials, a double pipe structure was adopted. The nuclear and thermal analysis were carried out by a nuclear-thermal-coupled code, ANIHEAT and DOHEAT so that blanket materials were appropriately arranged to satisfy the acceptable operation temperatures. The temperatures of materials were kept in appropriate range for the neutron wall load $P_n = 5\,\mathrm{MW/m^2}$. It was found that the local TBR of WCLL with Be blanket was comparable with that of solid breeder blanket.

Keywords: blanket design, water-cooled lithium lead, DEMO, neutronics, thermal analysis

DOI: 10.1585/pfr.6.2405053

1. Introduction

For demonstration of fusion power generation, the engineering feasibility of blanket is a key issue. Conceptual design of a water-cooled solid breeder (WCSB) blanket for a fusion DEMO reactor, SlimCS has been studied [1]. The SlimCS is a compact tokamak reactor with a major radius of 5.5 m, aspect ratio of 2.6, normalized beta of 4.3 and fusion output of 2.95 GW. The peak neutron wall load is expected to be 5 $\mathrm{MW/m^2}$ when the average neutron wall load is 3 $\mathrm{MW/m^2}$. In the present blanket for SlimCS, a simplification of blanket structure was proposed from viewpoint of engineering feasibility [2]. This proposed blanket structure is that Li_4SiO_4 (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. The subcritical water (23 MPa, 290-360°C) is one of the coolant options. The net tritium breeding ratio (TBR) of the reactor is required to be as high as 1.05 for self-sustainable operation as well as accumulation of startup fuel for the next fusion plant. Considering the effective blanket coverage and the lithium burn-up of the breeder, the required local TBR for SlimCS is estimated to be 1.41 to reach the net TBR of 1.05, which would be likely to be satisfied.

On the other hands, in DEMO next stage, advanced blanket option will be tested. In that case, one of the options is liquid lithium-lead (LiPb) breeder. Compared with solid breeder, LiPb breeder seems to have advantages of the sustainment of a design value of TBR without lithium burn-up and of a reduction of radioactive waste. The blanket concept in DEMO early stage would be WCSB blanket, considering replacement on cooling system, “water-cooled” would also be prime option for the next stage. In this study, as an advanced option for SlimCS blanket, conceptual design study of water-cooled lithium lead (WCLL) blanket was performed.

2. Design Target

In SlimCS, the conducting shell needs to be located at $r_w/a_p \leq 1.35$ for plasma positional stability and high beta access. Here r_w is the distance between the center of the plasma and the conducting shell, and a_p is the plasma minor radius. In the case of SlimCS with $a_p = 2.1$ m, when the gap between the separatrix and the first wall is about 0.2 m, the thickness of blanket is limited to about 0.5 m as shown in Fig. 1. Accordingly, the design target of this study is to satisfy the net TBR of ≥ 1.05 using the blanket with the thickness of 0.5 m. The blanket module size is a toroidal length of 1.2 m and a poloidal length of 0.6 m, which condition is same as the previous WCSB blanket concept in SlimCS. The cooling is only by subcritical water, and the LiPb is slowly circulated for tritium recovery.

3. Conceptual Design of WCLL Blanket

3.1 Preliminary analysis on WCLL blanket

The design point of WCLL was surveyed based on a mixture model. The neutron and gamma flux are calculated

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

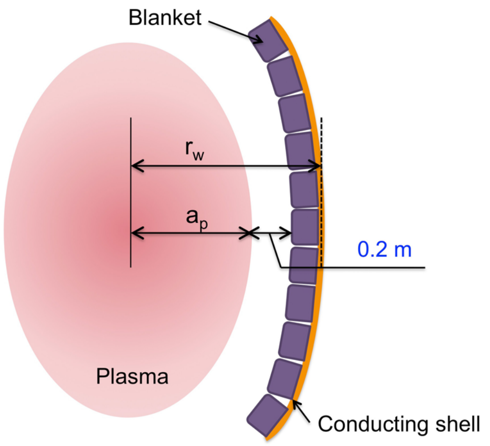

Fig. 1 Conducting shell concept.

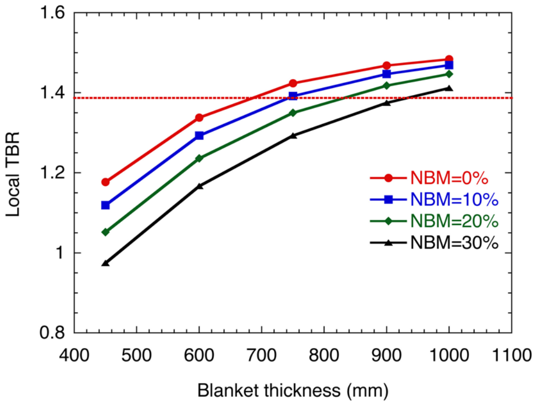

Fig. 2 Relationship between blanket thickness and local TBR.

by the one-dimensional transport code, ANISN [3], with the nuclear data library, FUSION-40 [4] based on JENDL-3.1 [5], and the nuclear heating rate and TBR are estimated using a neutronics calculation code, APPLE-3 [6]. The tritium breeder is lithium-lead ($Li_{17}Pb_{83}$ with 90% ^{6}Li enrichment). Figure 2 shows the calculated relationship between the blanket thickness and the local TBR. Here, "NBM" means non-breeder materials in mixture zone, that is consisting of a hypothetical mixed material composed 44% F82H and 56% coolant, which is equivalent to pipe outer diameter 12 mm, inner diameter 9 mm. As shown in Fig. 2, in SlimCS, the net TBR supplied from WCLL blanket was not enough because the thickness of blanket in SlimCS was limited to 0.5 m by conducting shell position for high beta access and vertical stability of plasma. Therefore, The beryllium (Be) pebble bed was adopted as additional neutron multiplier. Figure 3 shows the local TBR with the ratio of breeder (LiPb) and multiplier (Be pebble); LiPb/(LiPb+Be). The calculation assumed a packing fraction of 80% and blanket thickness of 0.5 m. As shown in Fig. 3, the WCLL blanket with Be has a potential for high TBR blanket on 0.5 m. In addition, local TBR becomes higher as ratio of Be increases. These results show that the higher TBR on WCLL blanket required a lot of beryllium.

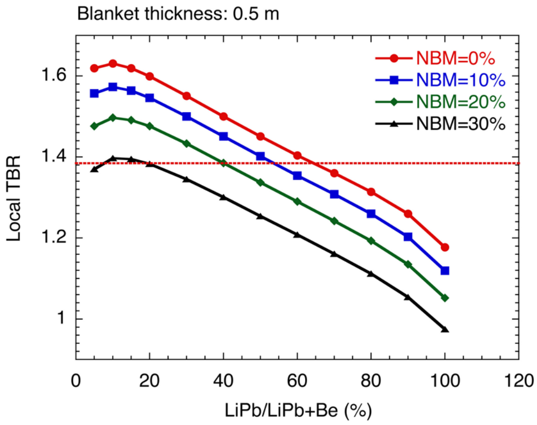

Fig. 3 Local TBR with ratio of LiPb and Be.

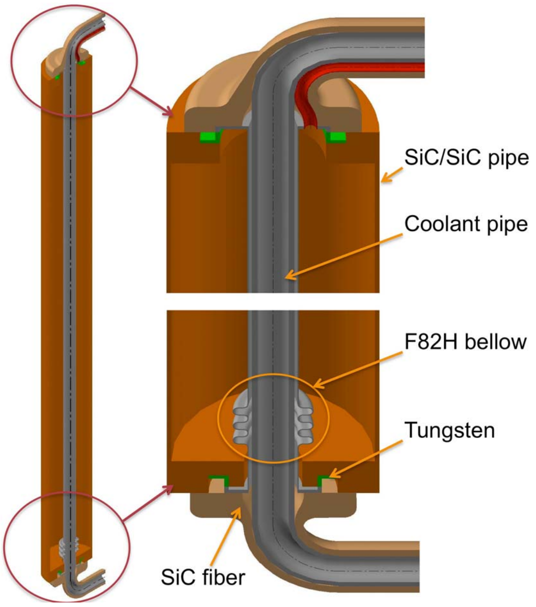

Fig. 4 Be unit with double pipe structure.

3.2 Conceptual design of WCLL blanket with Be

3.2.1 Be unit with double pipe structure

The separating from LiPb and efficiently heat removal are key issues in use of Be pebble. The upper operation temperature of Be (600°C) is higher than that of F82H (550°C). Therefore, SiC/SiC pipe was adopted as the boundary material of Be pebble and LiPb. The SiC/SiC pipe is not pressurized, and is only used as functional material (temperature boundary). Figure 4 shows the Be unit with double pipe structure to contain Be pebbles. The Be pebbles are separated by SiC/SiC pipe, and is cooled by coolant in the center. The coolant pipe is made of F82H as structure material. To avoid corrosion by high temperature LiPb ($\geq$ 480°C), the coolant pipe was covered by SiC fiber. The helium gas generated from Be is carried out via small tube made of F82 H. Inner F82H pipe and outer SiC/SiC pipe are welded via tungsten (W). Heat stress caused by difference in thermal expansion between F82H

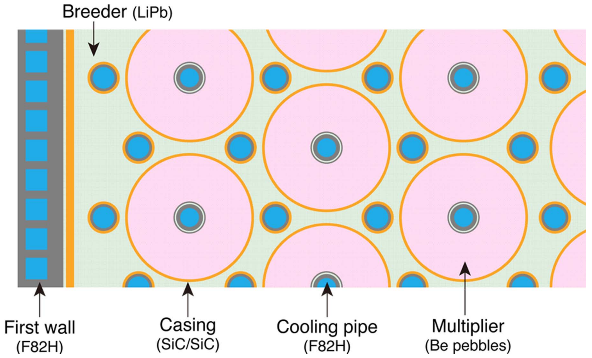

Fig. 5 Cross-section of WCLL blanket with Be.

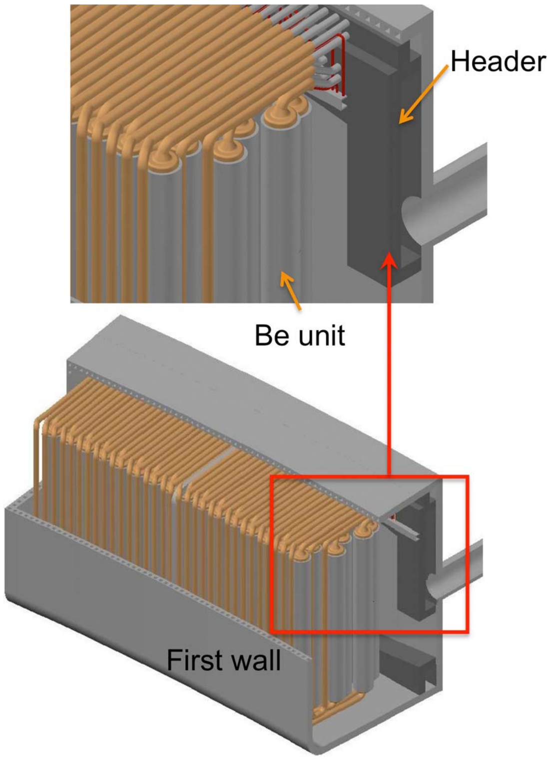

Fig. 6 Concept model of WCLL blanket with Be interior.

and SiC/SiC is absorbed by bellow structure. Figure 5 shows the cross-section of WCLL blanket with Be, and Figure 6 shows the concept model of WCLL blanket with Be interior. The blanket module is filled with LiPb, in which there are Be unit and coolant pipe for LiPb. The LiPb is cooled by cooling tube covered by SiC/SiC tube. For increasing Be pebble and preventing thermal input from LiPb, Be unit was arranged alternately and coolant pipe for LiPb was set in the gap of the Be unit. Since it is expected that the nuclear heating of LiPb near the first wall (FW) becomes higher, for keeping below 480°C, the SiC/SiC plate inner the FW made of F82H was preventing thermal input from high temperature LiPb breeder.

3.2.2 Coolant flow in poloidal direction

On previous concept of WCSB blanket in SlimCS, the coolant flows in the toroidal direction. On the concept of

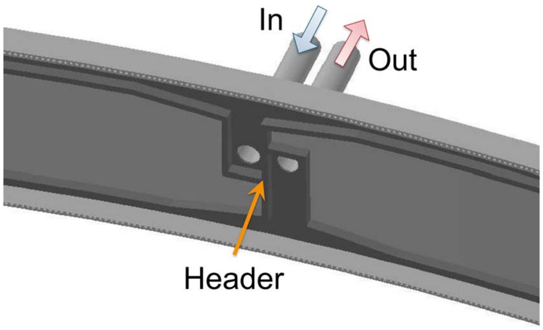

Fig. 7 Header structure on the back wall.

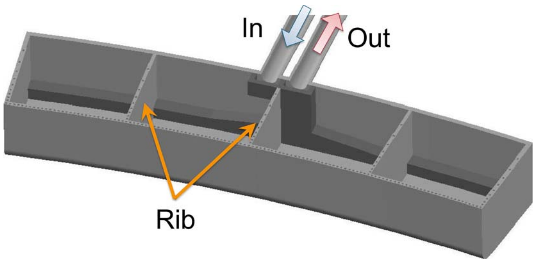

Fig. 8 Blanket module and ribs structure.

WCLL blanket with Be, large Be units are located, and the structure design of ribs passed by Be unit is very difficult on the blanket concept with large Be unit. So, the coolant flow in the poloidal direction was adopted. The poloidal coolant channel has advantages of lower coolant velocity and lower pressure drop of coolant compared with toroidal coolant channel because the poloidal coolant channel is shorter than the toroidal coolant channel. Figure 7 shows the header structure on the back wall. The coolant firstly flows through the FW channel and enters in the header which would flow through the LiPb breeder zones and the multiplier zones, finally, to the outlet. Figure 8 shows the blanket module and ribs structure. By locating flow channel in poloidal direction and using ribs (thickness of ~20 mm), sufficient strength of structure was ensured.

3.3 Neutronics and thermal calculation

On WCLL blanket with Be design, double pipe diameter is key parameter for high TBR. However, not only high TBR, it is essential element that the temperatures of the breeder, multiplier and structural materials need to be operated below upper operation temperature. The nuclear and thermal analysis were performed by a two-dimensional nuclear-thermal-coupled code, DOHEAT [7]. DOHEAT combines 2-D S_N transport code, DOT3.5 [8], with the nuclear data library, FUSION-40 based on JENDL-3.1, neutronics calculation code, APPLE-3 and 2-D steady-state heat transfer code. The DOHEAT code enables the evaluation for a more realistic model including cooling tubes, multipliers and breeders, and this code is suitable for calculation of the WCLL blanket with Be. The calculation conditions were as follows; $Li_{17}Pb_{83}$ was 90%^{6}Li enrichment,

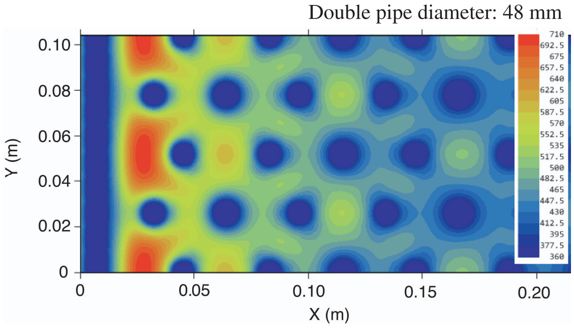

Fig. 9 Temperature distribution of WCLL blanket with Be calculated by DOHEAT.

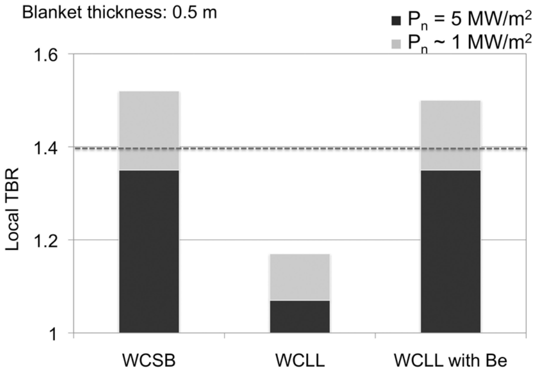

Fig. 10 Local TBR on WCSB, WCLL and WCLL blanket with Be in SlimCS.

a packing fraction of Be pebble was 80%, the temperature of coolant was 360°C (boundary condition on thermal calculation), the neutron wall load was 5 MW/m^2, and the heat flux from plasma was 1 MW/m^2. Figure 9 shows the temperature distribution of WCLL blanket with Be pebble on double pipe diameter of 48 mm calculated by DOHEAT. The temperatures of materials were kept below upper operation temperature. Figure 10 shows the local TBR on WCSB, WCLL without Be and WCLL blanket with Be in SlimCS. The local TBR of WCLL blanket with Be was similar to that of solid breeder blanket on the neutron wall load $P_n = 5\,\mathrm{MW/m^2}$. The neutron wall load has poloidal distribution. Pale bar in Fig. 10 shows the local TBR on the neutron wall load $P_n \sim 1\,\mathrm{MW/m^2}$. The calculated TBR increased with decreasing P_n. This is because the thickness of multiplier can be increased and the NBM including cooling pipe can be decreased by decrease of nuclear heating, as shown in Fig. 3. These results show that the WCLL blanket with Be concept seems to meet tritium self-sufficiency optimized in accordance with poloidal distribution of neutron wall load.

4. Summary

As an advanced option for SlimCS blanket, conceptual design study of water-cooled lithium lead (WCLL) blanket was performed. In SlimCS, the net TBR supplied from WCLL blanket was not enough because the thickness of blanket in SlimCS was limited to about 0.5 m by conducting shell. Beryllium pebble bed was adopted as additional multiplier. Considering of temperature of blanket materials, a double pipe structure was adopted. The local TBR of WCLL blanket with Be was similar to that of WCSB blanket on 0.5 m, WCLL with Be blanket has a potential for SlimCS blanket advanced option.

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