The text in the image is not visible due to the nature of the image. It appears to be a page from a scientific journal, likely related to fusion engineering and design. The text is not readable in its current form.
TBR comparison of water-cooled blanket based on PWR and SCWR water conditions

Japan Atomic Energy Agency, 801-1 Mukoyma, Naka, Ibaraki 311-0193, Japan

HIGHLIGHTS
- TBR is an insensitive value with the water condition variation.
- PWR water condition could be used as the coolant candidate for solid blanket.
- Pipe pitch is a key factor which could influence water fraction distribution.
- The layer thickness of beryllium is a dominant factor to affect TBR variation due to its neutron multiplication effect.

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A B S T R A C T
Nuclear analysis results were compared for water-cooled blanket based on PWR (pressurized water reactor) and SCWR (sub-critical water reactor) water conditions. The local TBR (tritium breeding ratio) in outboard zone was discussed in the range of $P_n$ (neutron wall load) from 1 MW/m$^2$ to 5 MW/m$^2$. It was found that water fraction has little impact on TBR, which is an important factor related to blanket tritium efficiency. It indicated that TBR value of each $P_n$ would be similar under the two kinds of water conditions, but PWR case is a little higher than that of SCWR's. In addition, it was found that beryllium is the dominant factor leading a higher TBR inside blanket. As a result, TBR is an insensitive value with the water condition variation. The results would be important to water condition choice for solid blanket in the future.

1. Introduction

SlimCS (central solenoid) was the conceptual design of a compact fusion DEMO reactor in JAEA [1]. In line with the reactor design, the DEMO blanket design was conducted with a water-cooled mode [2]. The blanket design was now underway to achieve sufficient TBR [3]. Presently, TBR variation with the neutron wall load, $P_n$ (MW/m$^2$) under different water conditions is concerned on due to the impact of changes in the proportion of blanket materials. In this paper, local TBR was compared with two kinds of water conditions in outboard zone, PWR and SCWR.

2. Blanket model concept

The water conditions are concerned for water-cooled blanket, because different water condition requires different design of water cooling system, and lead to the changes in the proportion of blanket materials. In particular, it is perhaps related to TBR variation. Presently, super-critical water (25 MPa, 280–510 °C), PWR (15 MPa, 290–330 °C), SCWR (23 MPa, 290–360 °C), and BWR (7 MPa, 275–285°C) are the kinds of coolant candidates. However, the super-critical water could lead to serious corrosion for FB2H material and high thermal expansion [4]. As to BWR condition, the steam flowing would be produced directly in the reactor core and needs lower pressure, but the steam is radiant and required relevant shielding. For engineering consideration, PWR and SCWR would be more close to DEMO conditions and be considered as the prior candidates.

Since the difference of heat removal capability of PWR and SCWR, for example, the coolant temperature rising (ΔT) from inlet to outlet of PWR case is 40 K, and the SCWR’s is 70 K, the layout of cooling loops would be different at the same $P_n$. Table 1 shows comparison of the two conditions at inlet temperature of 290 °C. Therefore, to remove the heat from blanket system sufficiently, PWR case only needs a short cooling loop compared to SCWR’s. In addition, to maintain the size of blanket module inside reactor under an inlet velocity of 4 m/s, the PWR case should be chosen as a poloidal cooling loop ($L \times W = 600 \text{ mm} \times 450 \text{ mm}$ in poloidal cross-section, Fig. 1a), and the SCWR case is a toroidal loop ($L \times W$ is 2000 mm × 450 mm in toroidal case, Fig. 1b).
3. Nuclear analysis

ANIHEAT code with the nuclear data library FUSION–40 was used for blanket nuclear analysis. It is a combined code of ANISN, neutronics and one-dimensional (1D) heat transport calculation resulting in the nuclear and the thermal analysis distribution [5]. The neutron wall load ($P_n$) would range in 1–5 MW/m$^2$. The outer and inner diameter of cooling pipe was chosen as 12 mm and 9 mm, respectively, in terms of the optimization. And the pressure drop would be under 0.5 MPa in the cooling system [6].

The 1D calculation model (as shown in Fig. 2) includes the FW channel, breeder, multiplier and F82H cooling pipes ($P$, number of cooling tube, is 1–8). The breeder and multiplier, for example, the beryllium zones, are cooled by cooling water using tubes of F82H, where the pebble bed contacts with the surface of tubes.

The layer thickness of breeder and multiplier is distributed by using $Li$ (1–10). The $Li$ (i=1–10) of each layer from plasma side to outward stands for the Li$_4$SiO$_4$, the beryllium and the Li$_4$SiO$_4$/Be$_{12}$Ti sequentially. L1–Li$_4$SiO$_4$, L2–beryllium, L3–Li$_4$SiO$_4$, L4–beryllium, L5–L10-Li$_4$SiO$_4$/Be$_{12}$Ti, and L1–L5 were the forward zones. The packing fractions of breeding zones (for example, Li$_4$SiO$_4$, isotopic content of Li is 90%) including mixed zones are 65%, and the packing fraction of beryllium is 80%. The material thickness of cooling pipe zone was calculated based on the pipe pitch including the water flow.

The pipe pitch was optimized with $P_n$ variation based on the WCO (water cooling optimization) code. It could optimize the coolant parameters for water-cooled blanket system. It was developed based on Fortran language under the design requirements of solid breeder blanket. It includes the “It files”, such as input data and output data, the nuclear heat library, and a excel file, which is related to a given $P_n$. An executable file, the piping, performs all the calculations, which could result in outlet parameters, such as the coolant velocity, the final water pressure, and the temperature.

![Fig. 1. Two kinds of cooling loops. (a) PWR and (b) SCWR.](image)

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PWR</th>
<th>SCWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$ (MPa)</td>
<td>15</td>
<td>23</td>
</tr>
<tr>
<td>$C_p$ (J/(kg K))</td>
<td>5256</td>
<td>5075</td>
</tr>
<tr>
<td>$\rho$ (kg/m$^3$)</td>
<td>745.4</td>
<td>757.7</td>
</tr>
<tr>
<td>$\mu$ (10$^{-3}$ Pas)</td>
<td>0.0293</td>
<td>0.0947</td>
</tr>
<tr>
<td>$K$ (W/(m K))</td>
<td>0.576</td>
<td>0.590</td>
</tr>
</tbody>
</table>

![Fig. 2. 1D layer model scheme.](image)

Table 2

<table>
<thead>
<tr>
<th>Pitch (mm) and WF (%) with $P_n$ (MW/m$^2$).</th>
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<tbody>
<tr>
<td>$P_n$</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>3</td>
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<tr>
<td>2</td>
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<tr>
<td>1</td>
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</tbody>
</table>

The water fraction (WF) is shown in Table 2 with the distribution of two water conditions based on pitch concept scheme (Fig. 3). It indicated that PWR cases have bigger pitch, but lower WF than that of SCWR’s.

The temperature limitation of blanket material are as following: F82H $\leq$ 550 °C; beryllium $\leq$ 600 °C; Li$_4$SiO$_4$/Be$_{12}$Ti $\leq$ 900 °C.

4. Comparison of local TBR

Local TBR was obtained in the outward board zones of blanket where the total blanket thickness is 450 mm. Since $P_n$ varied from 1 to 5 MW/m$^2$ with pipe pitches change, the local TBR varied correspondingly. It was found that the trend of the local TBR profile is a non-linear decreasing distribution while $P_n$ level is rising [7], as shown in Fig. 4.

Although the thickness of blanket would be kept the same as 450 mm, however, the nuclear heat inside blanket would be increased with $P_n$ rise, and the number of cooling tubes should be added to keep the temperature of breeder and multiplier as a normal level. Consequently, TBR would be dropped due to the decrease in nuclear material while structure material is decreasing. On the other hand, once blanket $P_n$ was varied, the thickness of breeder and multiplier should be changed accordingly; it also leads a variation to TBR for the thermal neutrons consideration.

In particular, TBR under the two kinds of water conditions would be similar to the relevant $P_n$. It indicated that the water fraction has little impact on TBR (Fig. 4). In addition, there is small gap between the two TBR curves. The TBR of PWR’s is a little higher than that of SCWR’s due to the layer thickness difference, especially for beryllium, which is a dominant factor to TBR in blanket.

![Fig. 4. Local TBR with the $P_n$.](image)
was found that all the layer thicknesses were increased to meet the temperature requirements at the $P_n$ decrease. Except for L2, beryllium, L1, L3, and L4 were almost the same for both water conditions. For L2, beryllium, the layer thickness of PWRs was bigger than that of SCWRs. This was the reason why TBR of PWRs was a little bigger than that of SCWRs, and the TBR would be affected so much with multiplier variation. It was confirmed by Fig. 6, which shows the total layer thickness of beryllium in the forward zones, L2 and L4.

In lower $P_n$, the layer thickness of beryllium is more than that of the higher $P_n$ for both water conditions (as shown in Fig. 5). It was one of the main reasons why TBR of lower $P_n$ was high compared to the high $P_n$’s.

For one more explanation, Fig. 6 is used to describe the thickness variation of beryllium with $P_n$. As shown in Fig. 6, in the SCWR, when $P_n$ was decreased down to 1 MW/m$^2$, the layer thickness of L2 and L4 would be increased to 86.5 mm and 65 mm, while L1 and L2 were chosen as 22 mm and 14 mm respectively, the corresponding $P_n$ is 5 MW/m$^2$. In this case, a big difference of TBR was 1.48 and 1.26 respectively, the same case as PWR condition.

However, the thickness of beryllium zone will not be more than 30 mm for multi-layer blanket. The explanation could show the influence of beryllium variation to TBR.

Obviously, compared to beryllium, Li$_4$SiO$_4$ would not contribute a positive function to the TBR rising when its layer thickness was also increased at the same magnitude. However, blanket TBR would be basically dependent on the isotopic content of lithium and neutrons, in which neutron bombard lithium yielding tritium. The reason is considered as the neutron multiplication effect by beryllium, which produces more neutrons in the forward zones, while the size of blanket was determined once the blanket concept was given. It is also found that the property of Li$_4$SiO$_4$ to TBR is restrained when its thickness is increased to some extent. Because when the size of breeder zone is increased, the multiplier zone would be decreased accordingly. It confirms that the neutron multiplication is first in the blanket system.

In a word, the variation of layer thickness would be changed so large in the forward zones compared to the backside zones. However, this should be under a given blanket dimension. In addition, the breeder and the multiplier should be under an optimal match ratio.

5. Summary

(1) The water fraction has little impact on TBR, which is insensitive value with the water condition variation. It is mainly dependent on the equivalent of isotopic content of lithium and neutrons.

(2) Nuclear analysis resulted in almost the same TBR under the two kinds of water conditions, but PWR is a little higher compared to the SCWR’s. This is the evidence that PWR water condition could be used as the coolant candidate for solid blanket in the future.

(3) The trend of the local TBR profile is a non-linear decreasing distribution while $P_n$ level rises not only because of the variation of structure material, but also due to the change of nuclear material for blanket thermal neutrons requirements.

(4) Pipe pitch is a key factor which could influence water fraction distributions and 1D blanket model establishment.

(5) The layer thickness of beryllium is a dominant factor to affect TBR variation due to its neutron multiplication effect, especially in the forward zones of blanket system. It would influence the detailed design so much in the forward zones for blanket system.

References


