A multi-layer breeding blanket concept for CFETR based on PWR condition

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Abstract—A breeding blanket concept with the multi-layer structure based on the PWR water-cooled condition was presented for CFETR. To explore the feasibility of the blanket scheme, the neutronics and hydraulics programs were carried out. It was found when the Pn is less than 3MW/m², the local TBR (tritium breeding ratio) would be in range of 1.46-1.7. Thus, the net TBR would be more than 1.05, which meets the tritium self-sustaining requirement for the fusion reactor. Especially, the local TBR is 1.66 at a neutron wall load (Pn) of 0.5 MW/m² and the corresponding net TBR is 1.21. On the other hand, it also clarified a pipe bore with 7-8 mm at an inlet velocity of 3-4 m/s would be suitable for the heat removal of the blanket module. In addition, the total pressure drop would be under 0.2 MPa in the cooling system. It was concluded that the blanket concept would be more effective and benefit to CFETR in view of its neutron wall load level and the tritium self-sustaining efficiency.

Keywords—water-cooled; breeding blanket; PWR; CFETR; TBR

I. INTRODUCTION

China Fusion Engineering Test Reactor (CFETR) would implement a 50-200MW fusion power in the future [1]. In order to verify the tritium self-sustaining issues, the breeding blanket schemes are ongoing now. It was reported that the water-cooled blanket has been developed for many years, so that it could be considered as one of the candidates for a fusion reactor [2−4]. However, the water conditions are diverse, such as the supercritical water, the sub-critical water, and the PWR condition, etc [5]. Recently, evidences have been found that PWR water has the benefit to be used as the coolant for a breeding blanket module from the point view of a fusion reactor level [6]. This is because of the acceptable TBR (tritium breeder ratio) for tritium self-sustaining efficiency and the compatibility with RAFM material [7]. As we known, the PWR water has long history in engineering application in the world, once it was chosen as the coolant for the blanket modules, the blanket engineering feasibility would be enhanced. In view of this, a breeding blanket concept using PWR cooling condition was taken account for CFETR.

In this study, the blanket concept was focused on, 1) the nuclear material choice, 2) the TBR issues, 3) the thermal hydraulics. The design and analysis were based on CAD, blanket neutronics and the CFD simulation technology.

II. BLANKET CONCEPT

A. Nuclear material design

For a breeding blanket, tritium self-sustaining efficiency has the priority among all the blanket issues, thus the nuclear material choice is necessary to satisfy the TBR requirement for the blanket plan.

Firstly, for the breeder, a Li4SiO4 pebble bed was applied due to its high density of 6Li (6Li enrichment attains 90%), which is thought of as a good breeder material for enhancing the TBR [8]. Because tritium is generated by reaction of Li and neutron, the blanket TBR would be determined by the reaction probability of neutrons and the Li material.

The blanket would be required the maximization of tritium generation. So the beryllium and the Be12Ti were chosen as the multiplier due to their good performance in neutron multiplication. Especially, the Be12Ti is applied as neutron multiplier due to its compatibility with the tritium breeder materials [9]. In addition, a research program indicated that the beryllium intermetallic compounds could be as the neutron multiplier due to their good chemical, thermal, mechanical, and irradiation property [10].

For the purpose of generating more tritium, the high density of 6Li zones was mainly in the area closed to FW channel because of the high neutron doses in these zones, which could enhance the reaction probability between neutrons and Li atoms. The same reason, beryllium was located in these zones for neutron multiplication. As we know, for a breeding blanket module, tritium would be generated largely due to the neutron multiplication in the zones near the plasma side.

In addition, Be12Ti and Li4SiO4 were mixed in the backward due to the chemical stability of Be12Ti, which could contribute to TBR increasing. Fig.1 shows the nuclear material allocations inside a blanket module [11]. Here, label Li (1) is first Li4SiO4 zone, Li(2) is the second Li4SiO4 zone, Be(i, i=1-2) is beryllium area. The backward area of the blanket module is filled with mixed pebble beds of Be12Ti&Li4SiO4.

B. Blanket cooling system

To match the PWR condition (15MPa, 290-330℃), the size of a blanket module was chosen as 0.6 m(L)×0.45m(W) in toroidal plane. The height of the blanket module in the poloidal direction would be depended on detailed engineering design in the future. The structure material of FW channel and...
the cooling tubes was chosen as RAFM steel, which has the compatibility with PWR water condition. The cooling system consists of FW channels and the cooling tubes [12]. The total length of FW channel was 2.02 m, and the maximum length of pipe circuits was 2.894 m. The equivalent diameter of FW channel was 11.3 mm and the pipe bore was 8 mm, the outer diameter of cooling tube was 10 mm. The heat removal capability would be confirmed in the thermal hydraulics simulation. Fig.1 shows the cross-section of the blanket module with cooling tubes.

![Fig.1 A cross-section of the blanket interior](image)

I. NEUTRONICS DESIGN

A. One dimension model for neutronics

As to tritium self-sustain issues, a 1-D neutronics program has been done using MCNP5, which could result in the blanket TBR based on the P_n range of 1-5 MW/m^2. This aim was to investigate the relationship between neutron wall load and the TBR with a varied pipe pitch (as shown in Table.1).

The nuclear materials were assigned according to the description in 2.1, which the Li(1) and Li(2) were for Li_4SiO_4, Be(1) and Be(2) were for beryllium blocks, and the remaining zones in the backward were set for the mixed pebble beds, the Be_{12}Ti& Li_4SiO_4.

<table>
<thead>
<tr>
<th>P_n (MW/m^2)</th>
<th>TBR</th>
<th>pitch (mm)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1.7</td>
<td>60</td>
</tr>
<tr>
<td>1.1</td>
<td>1.59</td>
<td>34</td>
</tr>
<tr>
<td>2</td>
<td>1.52</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>1.46</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>1.41</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>1.38</td>
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</tr>
</tbody>
</table>

Fig.2 Local TBR with P_n (MW/m^2)

B. Calculation and discussions

In the neutronics results, it was found the TBR was in the range of 1.38-1.7 at the P_n of 0.1-5 MW/m^2. Especially, the local TBR is 1.66 at the P_n equal to 0.5 MW/m^2, which is almost the average neutron wall load of CFETR. It was found that the P_n was equal to 3 MW/m^2 or lower, TBR would be more than 1.46, as shown in Fig.2.

It was reported, to meet the net TBR value of 1.05, the breeder area should cover 76% of the inner surface in vacuum vessel in the case of a single-null divertor. According to this method, the required local TBR would be 1.43 [13]. Therefore, when the P_n is under 3 MW/m^2, it would reach the requirement. In fact, the average neutron wall load of CFETR reactor is under 0.5 MW/m^2, thus the net TBR would be more than 1.21 corresponding to the local TBR equal to 1.66. In terms of this, even there is tritium deposition and the residue, the blanket has more favorable benefits and design margin to meet tritium self-sustaining efficiency.

In addition, the local TBR is as a function of nonlinear decreasing with the P_n variation. Since the pipe pitch was dropped down with the P_n rise, so the breeding area would be reduced comparing to the lower P_n cases. This is the direct reason causing the local TBR variation correspondingly. Therefore, once the CFETR assumes a P_n under 0.5 MW/m^2, the blanket pipe pitch in poroidal plane would be enlarged due to the lower nuclear heat induced by the dose of the neutron wall load. As a result, the breeding area is increased lead to a relative high value of local TBR.

Absolutely, it is not all the blanket modules assuming the average neutron wall load value, especially in poloidal direction of a 360° range [14]. Particularly, the neutron wall load distribution of CFETR would be in the range of 0.1-0.5 MW/m^2 in poloidal plane, the maximum appears in the equatorial zone in outside. The minimum is in the pole zones. Furthermore, since the overall TBR is generated by all the blanket modules inside vacuum vessel, so the blanket dimension, for example, like the radial thickness of the blanket module could be optimized according to the CFETR design criteria.

II. CFD SIMULATION

A. CFD model

The target of thermal hydraulics simulation was to explore the heat removal capability of the blanket module by using PWR condition. Therefore, the key concerns were on the followings, 1) whether the cooling system matches the PWR water condition or not, 2) the pressure drop must be under the design guideline. The CFD models include the FW channel circuits and the pipe circuits (pipe1 and pipe2).

To establish the CFD net model, the element hex/wedge was chosen in gambit modeling (CFD pre-processing) for the regular zones, meshing with cooper method. Boundary layers are set between the solid zones of RAFM tubes and the coolant zones. The absolute roughness of the inner surfaces of the cooling channels was chosen as 0.05. The double precision calculator was chosen for the slenderness ratio model for the turbulence calculation with a realizable K-epsilon mode.

The water properties: the density (kg/m^3), the specific heat capacity (J/kg-K), the thermal conductivity (W/m-K), and the viscosity (Pa-s) were chosen as the varied values with pressure changes.
and temperature variation, which could describe the dynamic properties of the water condition.

The total nuclear heat of neutron and gamma was loaded on the cooling system with an average value according to each $P_n$ level (1-5 MW/m$^2$). The heat flux on the surfaces of FW would be in the range of 0.5-1 MW/m$^2$ correspondingly. The inlet velocity of FW channel was chosen as 3 m/s.

**B. Results and discussion**

The CFD results indicated maximum temperature of RAFM steel was under 550°C, which is acceptable for the temperature limitation of structure material (Fig.3). The outlet temperature of FW channel is 314°C, this temperature value was used as the inlet data for piping circuits in the water the header. It was found the temperature rising in the FW channel and piping circuits were 24K and 16K respectively. It indicated that the FW channel assumed about 60% temperature rising in all the cooling system and was confirmed in past work. Because the high nuclear heat and heat flux in the zone closed to plasma.

For the outlet temperature of pipe circuits, the pipe1 was 329.16°C, pipe 2 was 328.49°C. This means that the temperature range of the whole cooling system matched PWR due to the lower $P_n$ level of CFETR. Blanket thickness could be reduced to an optimal dimension due to the breeding area reduction and causes the local TBR decreasing.

4) A multi-layer blanket module based on PWR water condition could be the candidate of the breeding blanket for CFETR, but it must be checked in detail in the engineering implementation.

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