Analysis of Time-Dependent Tritium Breeding Capability of Water Cooled Ceramic Breeder Blanket for CFETR∗

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Abstract Attaining tritium self-sufficiency is an important mission for the Chinese Fusion Engineering Testing Reactor (CFETR) operating on a Deuterium-Tritium (D-T) fuel cycle. It is necessary to study the tritium breeding ratio (TBR) and breeding tritium inventory variation with operation time so as to provide an accurate data for dynamic modeling and analysis of the tritium fuel cycle. A water cooled ceramic breeder (WCCB) blanket is one candidate of blanket concepts for the CFETR. Based on the detailed 3D neutronics model of CFETR with the WCCB blanket, the time-dependent TBR and tritium surplus were evaluated by a coupling calculation of the Monte Carlo N-Particle Transport Code (MCNP) and the fusion activation code FISPACT-2007. The results indicated that the TBR and tritium surplus of the WCCB blanket were a function of operation time and fusion power due to the Li consumption in breeder and material activation. In addition, by comparison with the results calculated by using the 3D neutronics model and employing the transfer factor constant from 1D to 3D, it is noted that 1D analysis leads to an over-estimation for the time-dependent tritium breeding capability when fusion power is larger than 1000 MW.

Keywords: WCCB, TBR, tritium surplus

PACS: 25.60.pj

DOI: 10.1088/1009-0630/18/8/13

(Some figures may appear in colour only in the online journal)

1 Introduction

The Chinese Fusion Engineering Testing Reactor (CFETR) is an ITER-like DT tokamak reactor. Corresponding to the roadmap of Chinese MFE (Magnetic Fusion Energy) development, the main missions of CFETR in phase I are to generate ~200 MW of fusion power, to demonstrate full cycle of tritium self-sufficiency with TBR≥1.0 and long pulse or steady-state operation with duty cycle time ≥ 0.3–0.5. The main missions of CFETR in phase II are to realize 1.2 GW fusion power, achieve TBR>1.1 and high electricity gain [1]. TBR is an important parameter to ensure full cycle of tritium self-sufficiency. As one candidate of the breeding blankets for CFETR [2,3], the water cooled ceramic breeder blanket (WCCB) concept is being designed and the calculated TBR of 1.14–1.16 at the beginning of operation has been assessed based on accurate 3D neutronics analysis [4].

In general, the TBR value calculated by the neutron transport code is an initial TBR value at the beginning of reactor operation, without considering Li consumption in breeder and material activation which can cause the neutron flux spatial distribution and material composition variations with time. Furthermore, they lead to TBR and tritium breeding capability variation with time. It is essential to survey time-dependent tritium breeding capability to provide accurate data for the dynamic assessment of full cycle tritium. L. W. Packer [5] and A. Aures [6] performed pioneering work on tritium self-sufficiency of the Helium Cooled Pebble Bed (HCPB) blanket for Europe’s demonstration power plant considering time-varying neutron flux spectra and material compositions. The tritium inventory and depletion of material were assessed, using a constant and a temporally varying neutron flux spectra. However, the neutron flux spectra in the HCPB blanket might be different from that in the WCCB blanket. Pu Yong [7] carried out a preliminary investigation on time-dependent TBR for the WCCB blanket of CFETR based on a 1D neutronics model with a varying neutron flux spectra and obtained an artificial time-dependent 3D TBR by using the transfer factor f(t), which is defined as the ratio of TBR3D(t) to TBR1D(t). In fact, the f(t) varies with operation time. However, in Pu’s analysis, the transfer factor

∗supported by the National Magnetic Confinement Fusion Science Program of China (Nos. 2013GB108004, 2015GB108002, and 2014GB119000), and by National Natural Science Foundation of China (No. 11175207)
f(0) at the initial time is assumed to be constant over the operation time. This might significantly result in uncertainties in predicting time-dependent TBR.

In this paper, based on a detailed 3D neutronics model, the time-dependent TBR and tritium breeding inventory were evaluated by the coupling calculation of transport code MCNP [8] and activation code FISPACT2007 [9] for the WCCB blanket of CFETR. The results were compared with Pu’s.

2 Calculation model, code, and method

2.1 Calculation models  
CFETR’s major radius is 5.7 m and minor radius is 1.6 m, with an elongation of 1.8–2.0, and triangularity of 0.4–0.8. The WCCB blanket employs a scheme of a modular blanket: 4 inboard blanket modules and 6 outboard blanket modules are arranged surrounding the plasma. The toroidal dimension for each module is allocated according to the toroidal segmentation of 11.25 degree. Based on the integrated geometry of CFETR concept design, a 3D neutronics model with 22.5 degree torus sector was developed. Fig. 1 shows a vertical cross section through the middle of the vacuum vessel (VV) ports and a horizontal cross section for the inboard and outboard side. In order to avoid homogenization, the breeding blanket modules were created to be detailed as possible, including the mixture breeder pebble beds, first wall (FW), cooling plates (CP), back plates (BP), stiffening plates (SP), and side wall (SW). There are 489 cells of mixture breeder pebble beds in this model. To reduce the calculation uncertainty caused by the neutronics model, each breeding blanket module employs a heterogeneous structure. The material composition of the breeding blanket is summarized in Table 1.

![Fig.1](a) Vertical cross section and (b) horizontal cross section of CFETR neutronics model

<table>
<thead>
<tr>
<th>Component name</th>
<th>Material composition</th>
<th>Component name</th>
<th>Material composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>FW W-armor</td>
<td>Tungsten 100%</td>
<td>CP1–CP2</td>
<td>Boiling water 39.68%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(density: 0.12 g/cm³)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RAFM steel, 60.32%</td>
</tr>
<tr>
<td>Side wall</td>
<td>H2O 20%, RAFM 80%</td>
<td>CP3–CP7</td>
<td>Saturated boiling water 39.68%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(density: 0.481 g/cm³);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RAFM steel, 60.32%</td>
</tr>
<tr>
<td>FW structure</td>
<td>Superheated steam: 25.3%</td>
<td>Reflector</td>
<td>H2Zr 100%</td>
</tr>
<tr>
<td>Mixed breeding</td>
<td>Breeder: Li2TiO3 18%</td>
<td>Stiffening plate</td>
<td>Saturated boiling water</td>
</tr>
<tr>
<td>pebble bed</td>
<td>Li6 enrichment 90%</td>
<td></td>
<td>39.68% (density: 0.481 g/cm³);</td>
</tr>
<tr>
<td></td>
<td>Multiplier: Be12Ti 82%</td>
<td></td>
<td>RAFM steel, 60.32%</td>
</tr>
<tr>
<td></td>
<td>Packing factor: 0.8</td>
<td>Be pebble bed</td>
<td>H2O 20%, RAFM 80%</td>
</tr>
<tr>
<td></td>
<td>100%, Packing factor 0.8</td>
<td>Back plate (BP)</td>
<td></td>
</tr>
</tbody>
</table>
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The D-T reaction rate per volume inside 50 magnetic surfaces in the plasma region was calculated based on the literature \cite{10} and magnetohydrodynamic (MHD) equilibrium calculation. The five magnetic surfaces were selected to form a five-nested neutron source for MCNP transport analysis. By normalization neutron source density, the five-nested neutron source intensities are 1%, 6%, 13%, 30%, and 50%, respectively.

The 14 MeV DT-source neutrons were born uniformly in one of the five source zones. The isotropic angular distribution and the neutron energy were from the Gaussian fusion spectrum.

2.2 Codes and nuclear data

The MCNP and IAEA (International Atomic Energy Agency) Fusion Evaluated Nuclear Data Library FENDL2.1 \cite{11} are employed to calculate the neutron flux spectra in each zone of blanket models. The fusion activation code FISPACT-2007 and the European Activation File (EAF-2007) library are used to perform the neutron-induced activation calculations of materials in each breeder cell of blanket modules and to determine Li burn-up in breeder and material composition change. The neutron energy spectrum employs 175 VITAMIN-J groups.

2.3 Calculation method

A coupling MCNP and FISPACT code was developed, the flow chart is shown in Fig. 2. In step 1, TBR(0) and the energy spectrum of each breeder cell of blanket modules at the initial time were calculated by the MCNP code, and then, the initial neutron spectra were input to the FISPACT to obtain the activation information after an irradiation time-step; in step 2, the material information was updated based on the obtained activation information, the MCNP code was used again to acquire the updated TBR and neutron spectra. Then the same process from step 1 to step 2 was repeated again, and when the Li burn out in the breeder or the simulated time was over the set time, the iteration would be stopped.

In this analysis, some assumptions are listed as follows.

a. The neutron energy spectrum, material composition in each cell, Li burn-up, and TBR values were assumed to be constant during a time step.

b. CFETR operation scenario was a steady state with the duty time factor of 0.5, and the time step was set as 0.5 year, the effective activation time in each time step was defined as the product of the duty time factor and the time step.

c. Produced tritium was either directly consumed or stored in the effective activation time in each time step. In addition, tritium decay was taken into account after the effective activation time.

d. All H and He isotopes were directly extracted from the blanket, the collapsed cross sections of $^3$H(n, 2n)$^2$H and $^3$He(n, p)$^3$H were set to zero in FISPACT \cite{5}.

e. The tritium retention in material was not considered.

Based on the above assumption, the dynamic tritium surplus in n time step can be calculated by following three equations:

$$TS(n) = TSir(n) \times DFur(n),$$

$$TSir(n) = (TBR(n) - 1) \times NS(n) \times \frac{T^2_1}{ln2} + (TS(n) - 1)$$

$$-((TBR(n)-1) \times NS(n) \times \frac{T^2_1}{ln2}) \times e^{ln2 \times TSir(n)/T_{1/2}},$$

$$DFur(n) = \exp(-ln2 \times Tit(n) \times (1 - DF(n))/T_{1/2},$$

where, $TSir(n)$ is the tritium surplus in the effective irradiation time in n time step, $DFur(n)$ is the correction factor of tritium decay, i.e. free decay from effective irradiation time to the end of n time step is considered. $DF(n)$ is the duty time; $T_{1/2}$ is the tritium half life; TBR(n) is the TBR value in n time step; NS(n) is the neutron number generated in per unit time in plasma chamber; and $Tit(n)$ is the effective irradiation time in n time step.

![Fig.2 Flow chart of coupling MCNP and FISPACT code](image)

3 Results and analysis

3.1 TBR dependent on operation time and fusion power

The 3D TBR (TBR$_{3D}$) values were calculated under 50 MW, 200 WM, 1000 MW, and 3000 MW fusion power over 10 operation years, respectively. Fig. 3 shows TBR$_{3D}$ as a function of operation time and
fusion power. For 50 MW fusion power, TBR_{3D}(5) is 1.1404 and TBR_{3D}(10) is 1.1401, TBR reduces 0.04% and 0.06%, respectively. For 200 MW fusion power, TBR_{3D}(5) is 1.1394 and TBR_{3D}(10) is 1.1390, TBR reduces 0.12% and 0.25%, respectively. For 1000 MW fusion power, TBR_{3D}(5) is 1.1333 and TBR_{3D}(10) is 1.1250, TBR reduces 0.65% and 1.38%, respectively. For 3000 MW fusion power, TBR_{3D}(5) is 1.1156 and TBR_{3D}(10) is 1.0722, TBR reduces 2.21% and 6.01%, respectively. It is noted that TBR decreases with operation time and fusion power increase. This decrease is very slow when fusion power is from 50 MW to 200 MW and it is fast when fusion power is higher than 1000 MW. This is because Li burn-up in the breeder is proportional to fusion power in the same operation time. In addition, assuming blanket lifetime is 10 years, the TBR value is greater than 1.1 when fusion power is lower than 1000 MW; however, when fusion power is 3000 MW, the TBR value is smaller than 1.1 after 6 operation years. So the blanket lifetime should be less than 10 years when fusion power is higher than 3000 MW.

3.2 Tritium surplus variation over time

The whole tritium cycle system includes production in the blanket, consumption in the plasma chamber, retention in material, and penetration in coolant and environment, processing in tritium plant and so on. There are many factors impacting on the tritium self-sufficiency. In this paper, it is limited in blanket to analyze the time-dependent tritium breeding capability. It only considers time-varying neutron flux spectra and material compositions affecting the tritium surplus. The tritium surplus in each time step was calculated by post-processing based on Eqs. (1)–(3) which take into account the tritium decay and consuming in the plasma chamber due to the D-T reaction. Fig. 4 shows the curve of the tritium surplus variation over 10 operation years under different fusion powers. It is noted that the tritium surplus increases with the fusion power increase while the tritium surplus increasing rate gradually decreases with operation time due to the TBR decrease with operation time. Corresponding to 50 MW, 200 MW, 1000 MW, and 3000 MW fusion power, the tritium surpluses are 1.7681 kg, 7.016 kg, 33.433 kg, and 83.6194 kg during the 10 operation years, respectively.

3.3 3D model’s result compared with 1D’s

In a 1D calculation [7], the neutronics model is a sphere model. Apart from there being no cover plates and side walls, the radial building of the blanket in the 1D model remains consistent with the 3D one, and the material composition used in the 1D model is the same as those in the 3D model. For comparison purposes, Figs. 3 and 4 also show the results of the 1D calculation used in Ref. [7]. The transfer factor $f(t)$ which is defined as the ratio of $TBR_{3D}(t)$ to $TBR_{1D}(t)$ was calculated. Fig. 5 shows the real curve of the transfer factor $f(t)$ which is a function of operation time and fusion power. It is observed that the transfer factor $f(t)$ decreased with operation time and fusion power increase. When fusion power is 50–200 MW, the transfer factor $f(t)$ decreased very slowly with the operation time increase. However, for 3000 MW fusion
power, the maximum decrease of the transfer factor \( f(t) \) reached 4\%. In addition, the tritium surpluses calculated by using the 3D neutronics model were 0.1\%, 0.43\%, 2.78\%, and 12.61\% less than those calculated by using the 1D neutronics model plus the transfer factor. It is indicated that there is an over-estimation of TBR and tritium surplus by using the 1D neutronics model and transfer factor. The difference becomes larger when the fusion power is more than 1000 MW. This is because the geometry effect makes the decrease of TBR\(_{3D}\) and TBR\(_{1D}\) disproportional.

4 Conclusion

Based on a detailed 3D neutronics model, the time-dependent TBR and tritium surplus for the WCCB blanket were evaluated by the coupling calculation of MCNP and FISPACT, which uses the 175 group energy format and 0.5 years time step. The tritium decay was considered during calculation of the tritium surplus. The purpose is to provide an accurate data of the WCCB blanket tritium producing capability for dynamic modeling and analyses of the tritium fuel cycle.

The results indicated that the TBR and the tritium surplus is a function of operation time and fusion power. Corresponding to 50 MW, 200 MW, 1000 MW, and 3000 MW fusion power for CFETR phase I and phase II, in 10 operation years with a duty time of 0.5, the WCCB blanket TBR of 1.1408 at the initial time decreases to 1.1401, 1.1390, 1.1333, and 1.1250, respectively. The tritium surplus is 1.7681 kg, 7.016 kg, 33.4333 kg, and 83.6194 kg, respectively.

By comparison with the calculation using the 1D model with a constant transfer factor, the 1D result has an over-estimation for the time-dependent tritium breeding capability when fusion power is larger than 1000 MW. However, it has a little impact when fusion power is at the range of 50 MW to 200 MW.

References


(Manuscript received 8 September 2015)
(Manuscript accepted 28 December 2015)
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