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Preliminary structural design and thermo-mechanical analysis of helium cooled solid breeder blanket for Chinese Fusion Engineering Test Reactor

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HIGHLIGHTS

- A helium cooled solid breeder blanket module was designed for CFETR.
- Multilayer U-shaped pebble beds were adopted in the blanket module.
- Thermal and thermo-mechanical analyses were carried out under normal operating conditions.
- The analysis results were found to be acceptable.

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ABSTRACT

With the aim to bridge the R&D gap between ITER and fusion power plant, the Chinese Fusion Engineering Test Reactor (CFETR) was proposed to be built in China. The mission of CFETR is to address the essential R&D issues for achieving practical fusion energy. Its blanket is required to be tritium self-sufficient. In this paper, a helium cooled solid breeder blanket adopting multilayer U-shaped pebble beds was designed and analyzed. Thermo-mechanical analysis of the first wall and side wall combined with breeder unit was carried out for normal operating steady state conditions. The results showed that the maximum temperatures of the structural material, neutron multiplier and tritium breeder pebble beds are 523 °C, 558 °C and 787 °C, respectively, which are below the corresponding limits of 550 °C, 650 °C and 920 °C. The maximum equivalent stress of the structure is under the allowable value with a margin about 14.5%.

1. Introduction

In order to narrow the R&D gap between ITER and fusion power plant, the Chinese Fusion Engineering Test Reactor (CFETR) [1–3] was proposed with primary objectives to demonstrate 50–200 MW fusion power, to achieve 30–50% duty cycle and an overall blanket tritium breeding ratio (TBR) no less than 1.2. The TBR requirement is recognized to be the most challenging for blanket design due to the restrictions of the available blanket material properties, and the limited space for blanket provided in CFETR. Tritium breeding performance of blanket in turn depends strongly on the structural and thermal hydraulic design.

A helium cooled solid breeder blanket concept was introduced for the superconducting tokamak option of CFETR. A TBR of 1.58 has been calculated in one-dimensional neutronics analysis. Accompanied with the process of three-dimensional neutronics assessment, structural design of the blanket has been carried out followed the applicable requirements specified in the systems requirement document of the ITER Test Blanket Modules System [4]. In this paper, the basic structure of the equatorial outboard module and the flow schemes of coolant and purge gas were introduced. Preliminary thermo-mechanical analysis of the first wall and side wall (FW & SW) together with breeder unit (BU) under normal operating conditions was reported.

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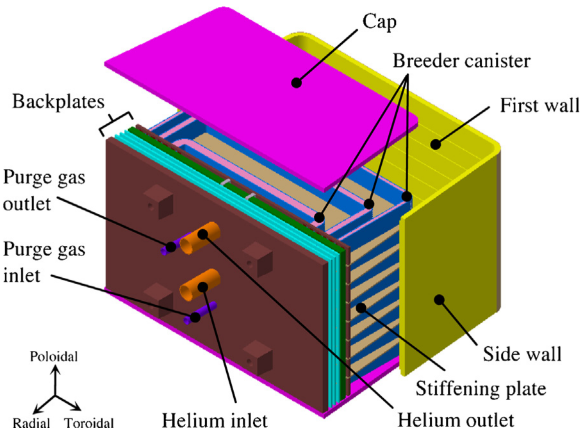

Fig. 1. Schematic view of the equatorial outboard module.

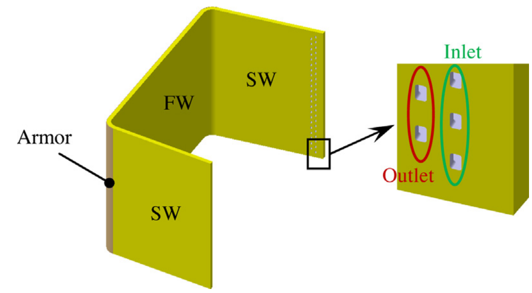

Fig. 2. Schematic of the FW & SW.

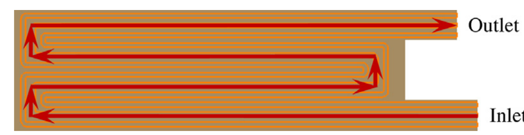

Fig. 3. A group of cooling channels in SP.

2. Structural design

2.1. Basic structure

The plasma chamber of CFETR is envisioned having 32 toroidal sectors with identical toroidal angular width (11.25°). Each toroidal sector contains seven inboard and eight outboard blanket modules, not taking into consideration the space occupied by heating or diagnostic systems. The poloidal heights of the modules are set as 960 mm. The radial thicknesses of the inboard and outboard modules are 450 and 800 mm, respectively. The remaining spaces behind the modules are mainly used to accommodate pipes, mechanical attachments and shielding blocks.

Fig. 1 shows the schematic of the equatorial outboard blanket module. The structural material of the module is Reduced Activation Ferritic Martensitic (RAFM) steel [5]. A FW, two SWs, two caps and several backplates make up the outer shell of the module. The module has 800 mm radial thickness. The FW and the outermost backplate are 1448 mm and 1606 mm in toroidal width, respectively. Seven radial–toroidal stiffening plates (SPs) are welded on the FW and SWs with the same spacing so as to strengthen the blanket structure. And also, the SPs have built-in cooling channels, which is helpful to remove the heat deposited in their own structures and the adjacent pebble bed regions. The BUs are placed in the spaces defined by the SPs. In the rear of the module are the manifolds formed by backplates for gas distribution and collection. The main design parameters of the blanket module are summarized in Table 1.

2.1.1. FW & SW

FW is a plasma facing component, each end of which connects with a SW, forming a U-shaped structure. A total of 45 U-shaped cooling channels with cross section of 15 mm × 15 mm and pitch of 20 mm are parallelly arranged inside the structure. The channel inlets and outlets are located at the inner faces of the SWs (see Fig. 2). To avoid excessive stress concentration, the channels have 2 mm fillet radius. The thicknesses of the walls are 28 mm. The front and rear wall of the channels are 3 mm and 10 mm in thickness, respectively. The coolant in the adjoining channels has opposite flow directions so as to achieve a more nearly uniform temperature distribution in the structures. In addition, a 2 mm thick tungsten layer was assumed to be installed on the front surface of the FW as armor.

2.1.2. Cap and SP

All of the caps and SPs are in the radial–toroidal plane, whereas the former are much thicker than the latter. With the identical manifolds and similar heat loads, the cooling channels adopt the same structure (see Table 1). Eight groups of channels are built into each SP. As shown in Fig. 3, each group of channels is made up of three cooling channels in parallel and that contains three U-turns. The cross sections of the channels are 4 mm (poloidal) × 6.5 mm and the pitches are 14.5 mm. The thickness of the two side walls of the channels are 2 mm, while that of the caps are 12 mm.

2.1.3. BU

The poloidal heights of the BUs are 106 mm. As shown in Fig. 4, each BU consists of three different sized U-shaped canisters for filling lithium ceramic pebbles (Li_4SiO_4) as tritium breeder. The packing factor of the breeder is about 62%. The radial thicknesses of the pebble beds are listed in Table 1. Each canister is made of two cooling plates (CPs) and closed by two steel wrappers. The U-bends of the canisters are positioned behind the FW. The two ends of the

Table 1
Main structural parameters of the blanket module.

	Parameters
Module size	960 mm (poloidal) × 800 mm (radial) × 1448–1606 mm (toroidal)
FW & SW	Thickness: 28 mm (3/15/10); cooling channel: U-shaped, cross section 15 mm × 15 mm, pitch 20 mm, fillet radius 2 mm Armor: thickness 2 mm
Cap	Thickness: 28 mm (12/4/12); cooling channel: W-shaped, cross section 6.5 mm × 4 mm, pitch 14.5 mm, fillet radius 0.5 mm
SP	Thickness: 8 mm (2/4/2); cooling channel: W-shaped, cross section 6.5 mm × 4 mm, pitch 14.5 mm, fillet radius 0.5 mm
BU	Pebble bed: radial thickness 20/15/180/30/200/45/40 mm; poloidal height 106 mm Cooling plate: U-shaped, thickness 5 mm Cooling channel: cross section 6.1 mm × 2.6 mm, 5.7 mm × 2.6 mm, 3.4 mm × 2.6 mm, 3 mm × 2.6 mm, 2.2 mm × 2 mm, 1.8 mm × 2 mm; pitch 10.1/9.7/6.4/5/17.2/25.8 mm; fillet radius 0.5 mm Wrapper: thickness 1.5 mm Baseplate: thickness 15 mm
Backplates	Thickness: 35/10/10/10/40 mm