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Thermal hydraulic responses of the Primary Heat Transfer System of the WCCB blanket to accident cases for CFETR

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HIGHLIGHTS

- The Primary Heat Transfer System of the WCCB blanket for CFETR was designed and modeled using RELAP5 code.
- Three typical accident cases, loss of flow accident, in-vessel loss of coolant accident and ex-vessel loss of coolant accident were simulated and analyzed.
- No serious damage was caused during the loss of flow accident due to the establishment of natural circulation of coolant.
- The integrity of the confinement barriers can be ensured for a limited period of time during loss of coolant accidents.
- Additional safety facility are needed to prevent serious consequences and mitigation methods are discussed.

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ABSTRACT

The Water Cooled Ceramic Breeder (WCCB) blanket is one of the blanket candidates for Chinese Fusion Engineering Test Reactor (CFETR). In this work, the Primary Heat Transfer System (PHTS) of the WCCB blanket was designed based on the configuration of the blanket sectors, employing two identical loops at this stage. Each loop consists of a steam generator, a pressurizer and two pumps, feeding water coolant into each blanket modules individually of 8 blanket sectors. One of the loop was modeled using RELAP5/MOD3.3 under normal condition and accident cases. The operational mode of PHTS was carefully chosen so as to obtain a more stable hydraulic behavior under steady state, due to the anisotropy of geometry structures and heat sources. Enveloping accidental cases, including Loss of Flow Accident (LOFA), in-vessel Loss of Coolant Accident (LOCA), and ex-vessel LOCA, were selected to preliminarily evaluate the safety performance of the system. The results show that the integrity of the confinement barriers can only be ensured in limited period of time during LOCAs. Additional safety facilities are needed and mitigation methods: are discussed.

1. Introduction

Chinese Fusion Engineering Test Reactor (CFETR) is an ITER-like superconducting Tokamak, aiming to bridge from ITER to DEMO [1,2]. The Water Cooled Ceramic Breeder (WCCB) blanket is one of the blanket candidates for CFETR [3]. Under the fusion power of 200 MW, the Primary Heat Transfer System (PHTS) of the WCCB blanket is designed based on the first phase configuration of CFETR. The PHTS of the WCCB blanket will operate under the Pressurized Water Reactor (PWR) condition (15.5 MPa, 558 K/598 K). From the thermal hydraulic point of view, the PHTS should provide adequate cooling for the blanket modules and demonstrate energy conversion under steady state. The transient responses of the PHTS are crucial to identify the safety characteristics of the system under accident cases. In addition, mitigation measures and related safety systems should be developed based on the thermal hydraulic responses, to prevent the release of radioactive materials and to ensure the integrity of the confinement barriers. Therefore, the main purpose of this paper is to evaluate the thermal hydraulic safety performance of the PHTS under both steady state and typical accident cases, so as to provide foundation of safety system design. The PHTS has been modeled by RELAP5/MOD3.3 which is a system analytical code widely used in fusion reactors simulation for over 10 years [4–11].

The description of the PHTS and modeling process using RELAP5/MOD3.3 is presented in Section 2. Steady state results are shown in Section 3. In Section 4, three typical accidents, namely Loss of Flow Accident (LOFA), in-vessel Loss of Coolant Accident (LOCA) and ex-vessel LOCA, are displayed and the mitigation mea-

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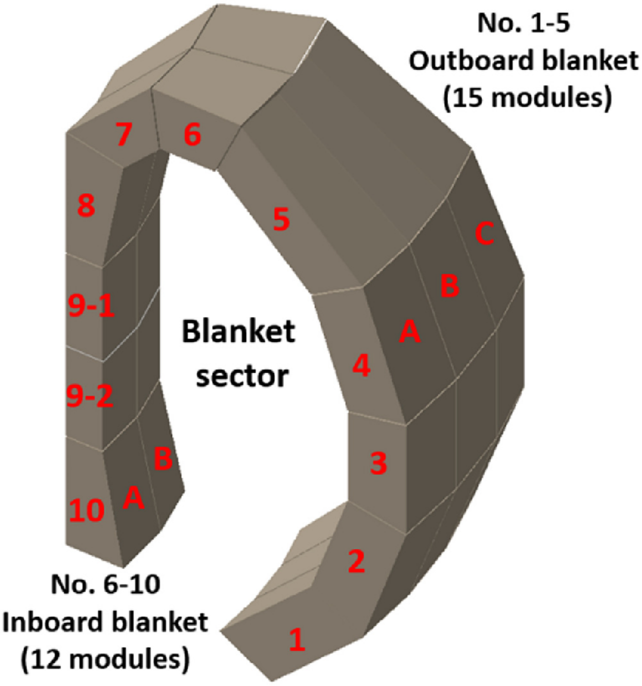

Fig. 1. WCCB Blanket sector design.

sures are also discussed. Finally, conclusions are presented in Section 5.

2. PHTS design and modeling

2.1. Description of PHTS

Based on the first phase design for CFETR, the configuration of one typical blanket sector (22.5°) has been segmented as shown in Fig. 1. There are 5 outboard segments and 6 inboard segments numbered from 1 to 10. Specially, the original inboard Blanket 9 was split into two identical modules numbered as 9–1 and 9–2 at the poloidal direction for the purpose of better flow distribution among blanket modules. The detailed analysis can be found in the previous work [12]. Each outboard segment consists of 3 identical blanket modules, namely A, B and C, while each inboard segment has 2 identical blanket modules A and B. Each blanket module has different geometry, position and nuclear heat. So each module has been designed individually. As the radial builds are similar for the 11 blanket modules, Blanket 3 is taken as an example [13] to demonstrate the structure details in Fig. 2.

The blanket module consists of a U-shaped First Wall (FW), a continuous and winding Cooling Plate (CP), Side Walls (SWs) and a Back Plate (BP). In addition, Stiffening Plates (SPs) are arranged in the radial-poloidal direction to strengthen the structure. The Breeding Zones (BZs) are multi-layered, inside which mixed pebble beds of $Be_{12}Ti$ and Li_2TiO_3 are used as breeding materials. To improve the Tritium Breeding Ratio (TBR), two layers of Beryllium pebble beds are employed as neutron multipliers. The Reduced Activation Ferritic/Martensitic (RAFM) steel is selected as structural material. On the plasma-facing surface of the FW, 2 mm of tungsten is coated. The allowable temperature limit is 1173 K, 873 K, 823 K and 1273 K for mixed pebble bed, Be pebble bed, RAFM steel and tungsten respectively [13–16]. The structural parameters of the 11 blanket modules are listed in Table 1. The sizes of the blankets are the average value along the three directions, since the blanket modules are not regular cuboids.

The PHTS locates in the Tokamak Cooling Water System (TCWS) Vault. The TCWS consists of PHTSs, the chemical and volume control system (CVCS), the drain and refilling systems, and the drying system. The PHTS loops include that for the Vacuum Vessel (VV), the WCCB blankets (BLK), the divertor (DIV). The PHTS of the WCCB BLK includes two identical loops. Each loop connects to 8 blanket sectors (22.5°*8) as shown in Fig. 3. Each blanket segment in the 8 sectors has respective sub-distributor and sub-collector for better flow distribution control, which is also in favor of safety isolation under accident scenarios. The Inboard Blankets (IBs) and Outboard Blankets (OBs) are fed separately considering the difference of heat generation and geometry sizes between them. The sub-distributors and sub-collectors for IBs/OBs joint to the mid-distributor and mid-collector respectively in each blanket sector [12]. Then the mid-distributors and mid-collectors of the 8 sectors joint to the main distributors and main collector (cold leg and hot leg). The schematic view of the multi-pipe manifolds design for one typical sector is shown in Fig. 4. The multi-pipe manifolds have different diameters as listed in Table 2. Then the mass flow to each blanket module is controlled by the different flow resistance along the pipe, avoiding the use of flow control valves.

The Steam Generator (SG), pressurizer (PRZ) and the pumps in the PHTS refer to the mature design of the PWR. Although the configurations of the reactor cores are different between the PWR and the CFETR, the water coolant systems operate both under pressurized water condition and the thermodynamic process is the same. Besides, it will be too demanding to design new system components for the PHTS of WCCB blanket, which requires extensive experimental verification. Therefore, it is considered feasible to learn from the PWR design at this stage.

2.2. RELAP5 model

One loop of the PHTS is modeled using RELAP5/MOD3.3. For simplification, the 3 (or 2) identical modules in one outboard (or inboard) segment are lumped as one module with triple (or double) original flow area. Nevertheless, the original flow path lengths and hydraulic diameters are remained to demonstrate the same hydraulic characteristics inside the blanket modules. As the cooling channels inside the blanket module are connected in series, the lumped blanket module is modeled as one pipe component. Design details of the blanket modules are modeled as much as possible, such as geometry sizes, radial builds, inclinations, nuclear heat and the layout of the multi-pipe manifolds, to indicate the influence of the anisotropic design features of the blanket modules [12]. The Blanket 4 of Sector 1 is taken as an example to indicate the RELAP5 nodalization as shown in Fig. 5. The modeling of other blanket modules uses the same method, while the inputs of heat sources and structural parameters are different.

The tungsten armor, structural material, Be pebble beds and the mixed pebble beds are modeled as layered rectangular heat structures in RELAP5. Each layer in the heat structure has its material properties and internal heat sources derived from neutronics analysis as listed in Table 3. In addition, the heat flux on the FW is assumed to be uniformly 0.5 MW/m^2 for CFETR. Therefore, the surface heat flux condition is added on the plasma facing side of the FWs. The surface heat flux multiplied by the triple (or double) original surface area of the FWs is listed in Table 3 as lumped surface heat for comparison. Moreover, convective heat transfer boundary condition is set up for the rest of the heat structures except for the rear side of the BP which is adiabatic boundary condition. Details of the heat structure can be seen in the previous work [17].

Fig. 6 shows the nodalization of one loop in the PHTS for WCCB blanket. The 8 sectors are all considered as standard blanket sector at this stage. Specially, the 8 sectors are modeled individually with different space angles and arrangements of multi-pipe manifolds.