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Numerical analysis of heat transfer in the first wall of CFETR WCSB blanket

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HIGHLIGHTS

- Detailed numerical analysis of heat transfer in a water-cooling first wall was carried out based on the conceptual design of CFETR WCSB blanket.
- Investigation of the influences of buoyancy effect and surface roughness on heat transfer in the water-cooling first wall was presented.
- Analysis of the effect of the front wall thickness on temperature was carried out for the water-cooling first wall design.
- Simulation results of two 1D CFD methods were evaluated by the 3D CFD data.

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ABSTRACT

China Fusion Engineering Test Reactor (CFETR), the first fusion reactor experiment project planned in China, is now being investigated in detail. Recently, a conceptual structural design of the Water-Cooled-Solid-Breeder (WCSB) blanket was proposed as one of the breeding blanket candidates for CFETR. In this research, based on the present design of the CFETR WCSB blanket, the heat transfer performance in the first wall (FW) under the pressurized water cooling condition was analyzed. The 3D computational fluid dynamics (CFD) results show that the maximal temperature of the FW will not exceed the limited temperature under normal or even higher heat flux condition. In addition, the effect of buoyancy on heat transfer is negligible under both conditions. The influence of roughness becomes increasingly important when the roughness height lies in the fully turbulent regime. The maximal temperature increases approximately linearly as the thickness of the front wall increases. It is also found that the heat flux and the local heat transfer coefficient are extremely non-uniform in the circumferential direction. Two 1D CFD methods are also evaluated by 3D CFD data, with the conclusion that both 1D results have some differences with the 3D data. The improved 1D method is more accurate than the former one. However, we ascertain that 1D methods should be used with caution for the water-cooling FW design.

1. Introduction

The China Fusion Engineering Test Reactor (CFETR) [1] will be the first fusion reactor in China. The CFETR aims at demonstrating fusion power and realizing tritium self-sufficiency. Recently, a conceptual structural design of Water-Cooled-Solid-Breeder (WCSB) blanket [2] was proposed as one of the breeding blanket candidates for CFETR. The first wall is one of the most important components of CFETR WCSB blanket. It faces the plasma and endures high temperature and intense irradiation. Thus, it is vitally important and necessary to evaluate the heat transfer performance.

The heat transfer performance in the FW is crucial for the cooling of the whole blanket due to its very high and extremely non-uniform heat loads. Much research concerning cooling performance of the FWs has been carried out in different kinds of blankets [3–14]. For the FW of Dual-Functional-Lithium–Lead Test Blanket Module (DFLL TBM), the influences of buoyancy on the flow and heat transfer of PbLi were analyzed by Ni et al. [7]. It was found that the flow field was significantly different with and without the buoyant effect, due to buoyancy-induced heat mixing. To improve cooling capacity, cooling channels with ribs were designed and analyzed in the DFLL TBM by Jin et al. [8]. For the Helium-Cooled-Pebble-Bed Test Blanket Module (HCPB TBM), extensive numerical studies have been performed in KIT, SWIP and others [9–11]. Recently, an experimental validation of the FW design for HCPB TBM was carried out in KIT [12,13]. Good consistency between computational temperature distributions and experimen-

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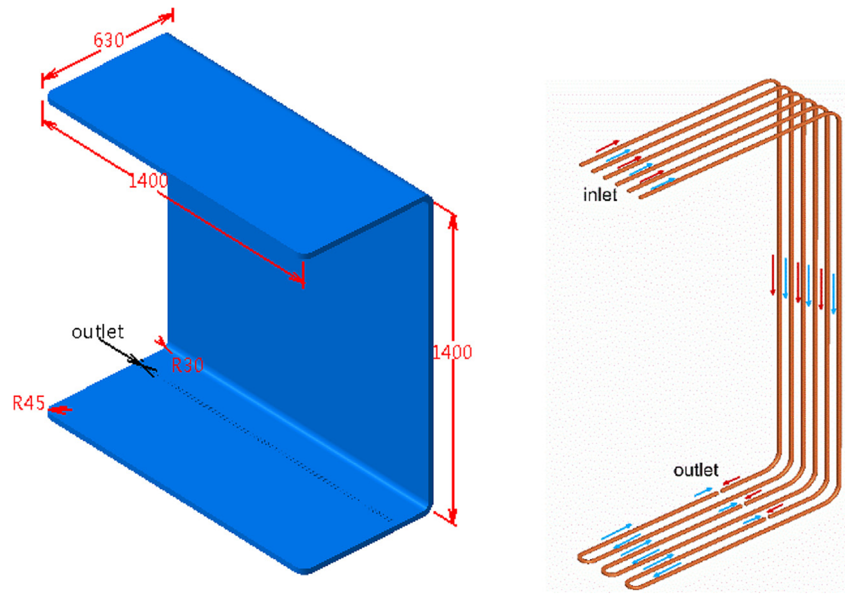

Fig. 1. The designed FW diagram for CFETR WCSB blanket.

Table 1
Thermal-hydraulic parameters.

Parameters	Value
Coolant pressure (MPa)	15.5
Coolant inlet temperature (°C)	280
Mass flow rate (kg/s)	0.0480
Heat flux from plasma (MW/m^2)	0.3/0.6
Heat flux from breeding zone (MW/m^2)	0.1
Volumetric heat sources (MW/m^3)	1.13

tal data validated the 3D CFD method. Also, it showed 1D CFD methods failed to predict the experimental temperatures due to the extreme asymmetry of heat loads. Nevertheless, most of the aforementioned work was based on helium or liquid PbLi coolant, and the detailed heat transfer analysis of a water-cooling FW is deficient. Therefore, the purpose of this study is to investigate the detailed heat transfer performance in a pressurized water-cooling FW based on the designed CFETR WCSB blanket.

In our study, simplified CFD geometry was firstly established based on the designed FW structure in the CFETR WCSB blanket. Then, the 3D CFD numerical method and two 1D CFD methods were introduced. Finally, detailed results and conclusions were given.

2. The FW structure of CFETR WCSB blanket

The FW is the plasma facing component, forming an U-shaped structure. The size of the FW is 1400 mm (poloidal) × 1400 mm (toroidal) × 630 mm (radial). There are 124 poloidal cooling channels arranged in parallel. The cross section of each channel is 8 mm × 8 mm and the space between them is 3 mm. Detailed dimensions of the geometry structure are presented in Fig. 1. Due to the symmetry of the structure, the simulation geometry can be simplified as seen in Fig. 2. As the plasma facing component, the FW endures high heat flux from the plasma and withstands volumetric heat sources from breeding zones, which were calculated by the neutronics code. The FW is cooled by pressurized water, and the flow in the square channels is vertical from top to bottom. Table 1 lists the series of thermal-hydraulic parameters and Table 2 shows the thermal physical properties of the coolant of pressurized water and structural material of Reduced Activation Ferritic/Martensitic (RAFM). Due to the small temperature changes in water, thermal

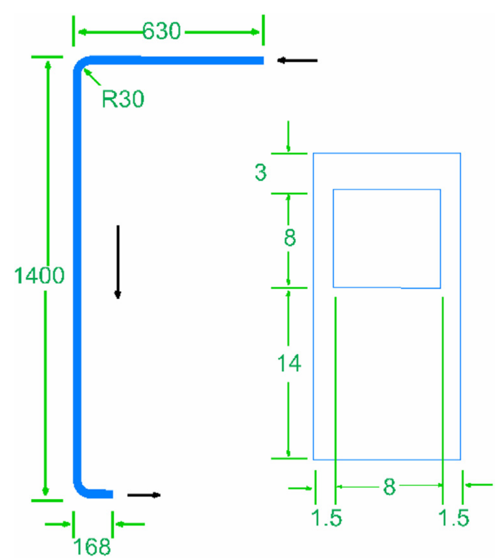

Fig. 2. The dimensions of simplified FW computational model.

Table 2
Thermal physical properties.

Properties	Coolant	Structural material
Density (kg/m^3)	764	7800
Specific heat (J/kg K)	5076	502
Thermal conductivity (W/m K)	0.596	32.2
Viscosity (kg/m s)	9.64×10^{-5}	
Thermal expansion coefficient (1/K)	0.0025	
Molecular Prandtl number	0.82	

physical properties of the coolant at the inlet are used in present simulations and the Boussinesq model is employed to analyze the effect of buoyancy on heat transfer.

3. 3D CFD numerical method and conditions

For the present CFETR WCSB blanket, the FW made of RAFM has built-in rectangular cooling paths and is cooled by 15.5 MPa pressurized water, which is widely used for fission reactors. Due