Numerical Analysis of Heat Transfer and Flow Field for CFETR Divertor

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Abstract. Nuclear fusion is now the ultimate need for energy, tokamak is one of the possible devices for controlled nuclear fusion. Based on the advanced tokamak magnetic confinement configuration and the research results of fusion physics in recent decades at home and abroad, Chinese Fusion Engineering Test Reactor (CFETR) will carry out innovative physical design to achieve the international requirements. Divertor is an essential component of the magnetic confinement fusion device, which directly sustains the strong particle flow and high heat load. The cooling system of divertor will directly affect whether divertor can function properly. In this paper, a new structure of divertor suitable for CFETR is designed and simulated, both the flow field analysis and the heat transfer analysis of the model were verified. The results show that the designed divertor structure can meet the system requirements.

Keywords: CFETR; Divertor; Heat load; Cooling system; Simulation

1. Introduction
The survival and development of human beings cannot be achieved without energy, and energy shortage and environmental pollution are the major problems facing human beings in the 21st century. In this context, controlled nuclear fusion, as one of the few sustainable energy sources that can meet large-scale applications, has been receiving extensive attention and research [1,2]. Based on its long-term energy needs, China officially joined ITER in 2006 to conduct fusion reactor-related engineering and physics research. The goal is to achieve a total fusion power of 1 GW for technical support of future demonstration fusion power plant (DEMO) [3].

Divertor is an important component in modern advanced magnetic confinement fusion devices important component. It serves to: discharge energy and particle flows from the fusion plasma; effectively shield impurities from the vessel wall to reduce contamination of the plasma; discharge products such as helium ash produced during the fusion reaction, and extract useful heat for power generation [4]. Plasma-facing components (PFCs) is the component in the divertor region that interacts directly with the plasma and is subjected to strong particle flow and high heat flow from the plasma, with a very harsh service environment [5]. PFCs' ability to withstand high thermal loads limits the maximum power of fusion reactor operation, which is directly related to cooling water system (CWS). According to the type of coolant inside divertor, it can be divided into water-cooled divertor and helium-cooled divertor, ITER has settled on the water-cooled divertor, as shown in figure 1. The Experimental Advanced Superconducting Tokamak (EAST) and CFETR divertor proposed to use water cooling as a baseline design concept.

EAST set a new world record on May 28, 2021, successfully achieving a repeatable 101-second
plasma operation at 120 million °C and 20-second plasma operation at 160 million °C, which is five times the original record of 20-second plasma operation at 100 million °C.

In CFETR, divertor is an important part of the first wall components, not only to take the responsibility of pumping and removing impurities, but also to be equipped with a cooling water system (CWS) to solve the heat load problem. The CWS of divertor is important for the long-term stable operation of divertor and even the whole device, so it is essential to verify whether divertor can meet the system requirements.

2. CFETR Divertor

CFETR is a new tokamak device developed after studying EAST and related research results at home and abroad, with a large radius of 7.2 m, a small radius of 2.2 m, a maximum circulating magnetic field of 6.5 T, and a first-wall water cooling system. Just like EAST divertor, CFETR divertor is also composed of inner vertical target (IVT), outer vertical target (OVT) and dome. The structure of target includes support, heat sink and the first wall material. But unlike EAST, CFETR does not have upper divertor, as shown in figure 2.
According to the cooling requirement evaluation of the CFETR divertor, it can be concluded that maximum flow rate, allowable pressure drop and allowable temperature increase of the divertor is 54 t/h, 5 MPa and 40 °C. In order to verify whether the CWS of divertor can meet the requirements, the relevant ANSYS-based simulations were carried out. CFETR divertor is shown in figure 3.

![Figure 3. CFETR divertor.](image)

3. Simulation Based on ANSYS
The fluid model of divertor is shown in figure 4.

![Figure 4. CFETR divertor flow filed.](image)

As shown in the figure 4, the flow of cooling water is “cassette-OVT- cassette-dome- cassette-IVT- cassette”, the entire fluid structure is basically a series structure, which ensures the uniformity of flow distribution to a certain extent.

The materials used in the analysis are KW, oxygen-free copper, ODS-Cu, and ODS-steel near to far. Fluid medium is water, inlet temperature is 140°C, The steady-state heat load applied to the striking point is 20MW/m².

3.1. Flow Field Analysis
The analysis results based on ANSYS are shown in the figures 5-8.
When the flow rate of divertor is 54 t/h, the flow field distribution inside the IVT, OVT, Cassette
and the whole divertor module is basically uniform. For IVT, pressure drop increases because of the small diameter of the cooling path of the remote operation interface, so the flow rate in this flow path is low. The flow rate of OVT suddenly gets larger because of the spoiler structure at the strike point. The pressure drop of IVT, OVT and cassette is 1.4MPa, 1.0MPa and 0.5MPa, which meet the design requirements, but the pressure drop of IVT is a little high and there is room for optimization. The total pressure drop of the whole divertor module is about 4MPa, which also meet the design requirement. The conclusions are shown in table 1.

| Divertor Region | Average Flow Rate (m/s) | Pressure Drop (MPa) |
|-----------------|-------------------------|---------------------|
| IVT             | 7.5                     | 1.4                 |
| Cassette        | 6                       | 0.5                 |
| OVT             | 7.6                     | 1                   |
| Dome            | 7.52                    | 0.87                |
| Whole Module    |                         | 4                   |

**Table 1.** CFETR divertor flow filed analysis (54t/h).

3.2. *Heat Transfer Analysis*

Heat transfer analysis requires consideration of nuclear heat. Nuclear heat based on CFETR fusion power of 1.5GW. The nuclear heat distribution is shown in figure 9.

![Schematic of nuclear heat](image)

**Figure 9.** Schematic of nuclear heat (MW/m³, fusion power of 1.5GW).

The flow rate of divertor is 54t/h, the heat flow density of the first wall at IVT and OVT is 20MW/m² in steady state (considering nuclear heat), temperature distribution cloud figures of IVT and OVT based on ANSYS are shown in figures 10-11, and the detailed calculation results are shown in table 2.

The analysis results of IVT show that the temperatures of KW, ODS-Cu and ODS steel are within the allowable range under the steady-state 20MW/m² (considering nuclear heat), and the highest temperature of ODS steel is located at the bolts and support legs, because there is nuclear heat influence here but the cooling capacity is relatively weak (mainly by conduction with the back plate connection).

The analysis results of OVT show that the KW and ODS-Cu are within the allowable range at a steady state of 20MW/m² (considering nuclear heat), but the maximum local temperature of ODS steel exceeds the allowable value, and the highest value is located at the main bolt and support leg, where the cooling capacity is relatively weak due to nuclear heat.
Figure 10. Temperature distribution cloud figure of IVT(54t/h,20MW/m²).

Figure 11. Temperature distribution cloud figure of OVT(54t/h,20MW/m²).

Table 2. CFETR divertor IVT and OVT heat transfer analysis (54t/h,20MW/m²).

|            | Maximum temperature of IVT(℃) | Maximum temperature of OVT(℃) | Permissible values(℃) |
|------------|--------------------------------|--------------------------------|------------------------|
| KW         | 1563                           | 1476                           | 1600                   |
| ODS-Cu     | 523                            | 600                            | 650                    |
| ODS steel  | 504                            | 1060                           | 600                    |
| Temperature rise | 39                      | 34.67                           | 40                     |

Figure 12 shows the temperature distribution of Cassette under nuclear heat, and the detailed calculation results are shown in table 3. Unlike IVT and OVT, situation of cassette is much more relaxed.
4. Summary
In this paper, a divertor design suitable for CFETR is presented and the associated model is built. ANSYS-based simulations were performed using the model. In order to demonstrate that the cooling system in this design can function effectively, both the flow field analysis and the heat transfer analysis of the model were verified.

(1) When flow rate of the whole divertor module is 54 t/h, The flow field analysis shows that the pressure drop of IVT, cassette, OVT and dome is 1.4MPa, 0.5 MPa, 1MPa, 0.87MPa. The total pressure drop of the divertor module is about 4MPa, which is less than the limit of 5MPa and meets the design requirement. Besides, there is still room for optimization.

(2) Under the consideration of nuclear heat, the steady-state heat (20MW/m²) transfer analysis shows that the divertor target can basically meet the exhaust heat demand and the temperature rise meets the requirement.

(3) The cassette temperature is within the allowable range when considering nuclear heat conditions.

The birth of new record on May 28, 2021 shows that China has taken another step forward in the field of nuclear fusion, and author hopes that CFETR will be completed soon to contribute to the progress of mankind.

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