Thermal analysis and optimization of the new ICRH antenna Faraday Screen in EAST

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In Experimental Advanced Superconducting Tokamak (EAST) experiments, to achieve long pulse and high-power ICRH system operation, a new kind of ICRH antenna has been designed. One of the most critical factors in limiting the operation of long pulse and high power is the intense heat load in the front face of the ICRH antenna, especially the Faraday Screen (FS). Therefore, the cooling channels of FS need to be designed. According to thermal-hydraulic analysis, the FS tubes are divided into several groups to achieve more excellent water cooling capability. The number of series and parallel tubes in one group is chosen as six. This antenna went into service in the spring of 2021, and it is delightful that the temperature distribution of the FS tube is below 400°C in 14.5 s and 1.8 MW ICRH system operation. However, the active water-cooling design was not carried out on the upper and lower plates of FS, which led to severe ablations on that region under long pulse and high power operation, and the temperature is up to 800. Therefore, the upper and lower side plates of the FS were designed with water cooling based on thermal-hydraulic analysis. During the 2022 winter experiments, the temperature of ICRH antenna FS was lower than 400 in the pulse of 200s and the power of 1 MW operation.

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1. Introduction

Ion Cyclotron Range of Frequencies Heating (ICRH) has been in operation in the Experimental Advanced Superconducting Tokamak (EAST) [1,2] for many years. ICRH system plays an essential role in auxiliary heating [3–5], with high performance in establishing and maintaining H-mode operation. And now the main objective of the ICRH system is to increase pulse time and improve the coupling efficiency between ICRH and plasma, a new ICRH antenna [6,7], which has low $k_A$ and better capability to heat the plasma, has been developed in the EAST. The new ICRH antenna system consists of RF transmitters, transmission lines, a matching system, a feed-through, and an antenna. It will launch 1.5 MW RF power during a 1000-s period between 25 and 70 MHz [8].

There are two ICRH antennas in EAST, which have been installed in port N and port I. The N-antenna and I-antenna have the same structure, and it’s position is shown in Fig. 1. The infrared camera-F and infrared camera-N monitor the temperature of I-antenna and N-antenna separately. Here, we only involve the thermal-hydraulic analysis of the N-antenna as the cooling structure of two ICRH antennas is similar. The structure of the new ICRH antenna is designed as shown in Fig. 2, which includes Faraday Screen (FS), current straps, vacuum transmission lines, and vacuum windows, which are actively cooled to transmit the MW level of RF power for a long pulse. This paper represents the design of cooling channels and the thermal-hydraulic of FS [9,10].

2. The design description of new ICRH front face components

Fig. 3(a) shows the detailed structure of the new ICRH front-face components. The poloidal current straps have two ports and one grounded location at the center. Besides, the carbon fiber carbon (CFC) lateral limiter can be in high performance to protect the antenna from particle bombardment. The FS protects the straps from direct exposure to the plasma environment and can polarize the electromagnetic wave for high heating of the plasma. It has been designed with three dimensions surface, which could be a better fit with the plasma. Fig. 3(b) shows the components of FS, which...
contains two side plates, a series of bars, the top plate, the bottom plate, the cover plate, and the central septum. The FS bars tilt angle to the horizontal is $7^\circ$ to fit the magnetic line of force in EAST.

The front components of the EAST ICRH antenna will endure two kinds of thermal loads:

- Plasma heat flux;
- Radio frequency loss on ICRH antenna.

Plasma heat flux: According to shot #107554, the EMC3-EIRENE [11] program has been used to calculate the plasma thermal flux on the antenna surface. By numerical simulation, the graph of thermal flux has been plotted and shown in Fig. 4. From the chart, the location of maximum thermal flux was at the top and bottom of the antenna, and the maximum value was about 0.25 MW/m$^2$. Besides, the minimum value was about 0.04 MW/m$^2$.

RF loss on EAST ICRH antenna: When the power transmits through the ICRH antenna, there will be RF loss generated by skin current effects. The formula for calculating the RF loss is as follows:

$$P = \frac{1}{2} I^2 \cdot R$$

$$R = \sqrt{\frac{\omega \mu_0}{2\sigma}}$$

In the above equations: $\omega$ is RF frequency, Hz; $\mu_0$ is permeability, H/m; and $\sigma$ is conductivity, S/m.

CST is used to simulate the RF loss on the 3D ICRH antenna. The total input power is 1.8 MW, and the material used for the antenna is stainless steel 316L. As shown in Fig. 5, the RF loss deposited on the FS tubes presents non-uniform distribution. The thermal load due to RF loss is relatively small compared to the plasma heat flux. For the convenience of calculation, it is assumed that the RF loss is uniformly distributed and the value is 0.02 MW/m$^2$, which is the maximum value calculated by CST.

During the design of the cooling system, the primary studies are listed as follows:

(a) The assessment of the flow rates in each component to prevent the dead flow zone. Meanwhile, the pressure drop between the inlet and outlet can’t exceed the pressure drop of the cooling system;
(b) Increase the heat transfer coefficient along cooling channels to improve the efficiency of heat convection in the high heat flux area.

According to the requirements of the FS cooling system, the maximum inlet pressure and outlet pressure are expected to be less than 2.5 bar and 1 bar, respectively, and the maximum inlet mass flow rate is 0.4 kg/s. Meanwhile, the temperature of the inlet is set...
to 30. ANSYS Fluent has been chosen to conduct the steady and transient analysis to simulate the performance of FS cooling. The realizable k-ε model is applied for the turbulent simulation.

There are 42 cooling channels in the half FS box. Considering the minimum pressure drop and uniform flow velocity distribution, the S-shape has been adopted as the cooling channel structure. As shown in Fig. 6, seven pipes are connected to the other half of the seven cooling pipes to form a cooling system combined in series and parallel. Also, the cooling channels of two side plates connect with the FS tubes.

Fig. 3. (a) The detailed structure of ICRH front face components; (b) Mechanical design of the Faraday Screen.

Fig. 4. Thermal load profiles in 1.8 MW of ICRH power as a function of different distance.

Fig. 5. RF loss on ICRH antenna, and the maximum value of FS is 0.02 MW/m².

The number of FS parallel is designed and optimized, and the cooling model is constructed and optimized to achieve the above goals. From all FS tubes in parallel to ten in a group, to five in a group and so on. The inlet and outlet pressure difference and minimum velocity of the above five models are calculated, and the results are shown in Table 1. It can be seen that with the increase in the number of parallel pipelines, the pressure difference between the inlet and outlet increases sharply. When five channels are in a group, the pressure difference is 1.6 bar, which exceeds the 1.5 bar required by the cooling system, and in some zones, the minimum velocity is 0.1 m/s. As also can be seen from Fig. 7(c), the decrease in the number of parallel pipes causes the speed of the first half of FS to increase sharply, resulting in a sharp rise in the flow resistance of the central septum. As a result, the flow velocity of the second half
FS pipe is minimal, which is easy to form dead zones, resulting in a greater chance of ablation of some FS pipes. Therefore, the scheme of five tubes in a group is abandoned. When the number of parallel pipelines increases, it can be seen from Fig. 7(a) that the flow velocity of most channels is minimal, and the flow velocity uniformity is very poor, so the scheme of ten pipelines and more pipelines as a group are abandoned. As shown in Fig. 7(b) and Table 1, when six FS tubes are in a group, the flow rate distribution is more uniform, and the pressure difference is less than 1.5 bar. Finally, a scheme of six pipelines in a group is adopted.

After the experiment on EAST, the data of antenna temperature shows that the temperature on the FS tube is lower than 400. However, large hot spots appear in the top plate of FS at high power. Therefore, water cooling should be carried out on the upper and lower plates to achieve the goal of a long pulse and high power. During the experiment, hot spots will most likely appear at the four corners. In addition, when designing the cooling circuit, the wall thickness should be greater than 5 mm to prevent water from entering the vacuum chamber. Therefore, the scheme with large rounded corners is adopted, as shown in the red circle in Fig. 8, and increases the reinforcement to ensure the stability of the upper and lower plates structure. Due to cooling system pressure drop and flow rate limitations in the FS, the cooling circuit of the top and bottom plates and the cooling circuit of the lateral limiters share the same inlet and outlet. The maximum pressure drop of lateral limiters is 5 bar. Meanwhile, the maximum inlet mass flow rate is 0.6 kg/s. Based on the ICRH antenna water cooling data, the top and bottom plates mass velocity is 0.1 kg/s.

Fig. 9 shows the velocity distribution and wall adjacent heat transfer coefficient (HTC) in the FS tubes under the mass velocity of 0.4 kg/s. It can be seen that the distribution of the rate is uniform. Besides, most cooling surfaces of FS have the HTC larger than $1.0 \times 10^4 \text{W/m}^2\text{K}$.

### 3. Thermal analysis of Faraday Screen and experiments of ICRH antenna conducted on the EAST

During the experiment in EAST in 2022, there were some critical issues. As shown in Fig. 10, the temperature of the top plate, which is made of stainless steel 316L, is relatively high in the red circle position. Fig. 11 shows shot #107554 at a power of 1.8 MW and a...
time pulse 14.5s, the highest temperature at the top plate of FS reaches 800, and the temperature was proportional to the time when there was no water-cooled in the top plate. It clarifies that the components of the ICRH antenna directly facing the plasma must have active water cooling. According to Chapter 2, plasma heat flux and RF loss are obtained. The thermal load distribution of FS is planned as follows to facilitate calculation:

(a) The thermal load is 0.25MW/m² at the position of FS poloidal distance greater than or equal to 20 cm, facing the plasma region;
(b) FS with the polar distance between –20cm and 20 cm, facing the plasma region, with a thermal load of 0.04MW/m²;

(c) The thermal load of FS departing from the plasma region is 0.02MW/m².

The temperature distribution on the surface of FS is obtained by coupling the fluid parameters obtained in Chapter 2 with the thermal load. In this paper, the calculation and simulation of whether there is an upper and lower plates cooling circuit are carried out, and the transient analysis of FS is carried out. The pulse width length is 200s. As shown in Fig. 12, the upper and lower plates' temperature is exceptionally high without water cooling, reaching up to 900, while the upper and lower plates' temperature with water cooling is only 300. In addition, Fig. 13 shows the temperature evolution of the upper and lower plates with time. It can be seen from the figure that, at about 60s, the temperature of the FS plates with a cooling loop (red line) tends to be stable, and the value is 300, while that of the upper and lower plates without water cooling (blue line) is linearly correlated with time and keeps rising.

After the waterway optimization two times, the ICRH antenna of window N was tested with a long pulse and high power. Due to the protection of the main limiter in Port I, the cooling structure of the upper and lower plates is not added temporarily. At shot # 119994, the power of the N-antenna is 0.8 MW, the power of the I-antenna is 0.2 MW, and the pulse length is 200s. The infrared camera data was used to plot the temperature of the top plate of the I-antenna

![Fig. 9. (a) The velocity distribution of FS; (b) The wall adjacent heat transfer coefficient distribution of FS.](image-url)

![Fig. 10. The temperature profiles on the front face of the ICRH antenna were measured by using an IR camera for the non-cooled top plate, and the temperature of the location circled by the red line was relatively high. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)](image-url)
and N-antenna, respectively, just as the red circle and yellow circle shown in Fig. 14(a) and Fig. 14(b). As shown in Fig. 14(c), the temperature of the I-antenna increases linearly with time, while that of the N-antenna is lower than 400. It is in good agreement with the simulation results. Therefore, the plasma-facing surface of the ICRH antenna need to have an active water-cooling structure to guarantee the safety operation of the antenna under a long pulse and high power.

4. Conclusions

To achieve the goal of a long pulse and high power of the ICRH heating on EAST, the cooling structure of the ICRH antenna has been designed and upgraded. Based on our calculation, a series and parallel cooling circuit consisting of six pipes are adopted to achieve
the uniformity of flow velocity distribution, and the wall adjacent heat transfer coefficient is larger than $1.0 \times 10^4$ W/m$^2$/k, which meets the requirements of the EAST cooling system. In addition, large rounded cooling water channels were used on the upper and lower plates to maintain temperature under 400 at the four corners of FS. And the reliability and safety of the cooling structure are shown in long pulse and high-power experiments on EAST.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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