



Research paper

Cooling circle design and testing for ITER radial X-ray camera

Sheng Zhang^{a,b}, Jian Ge^a, Bin Zhang^{a,b}, Liquan Hu^a, Yebin Chen^{a,*}, Kaiyun Chen^a, Jinlong Zhao^a, Juncheng Zhan^a

^a Institute of Plasma Physics Chinese Academy of Sciences, Hefei, 230031, China

^b University of Science and Technology of China, Hefei, 230022, China



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ABSTRACT

The ITER radial X-ray camera (RXC), which is installed in the middle diagnostics shield module (DSM) of equatorial port plug 12, is an important piece of diagnostic equipment in the tokamak system. A cooling circle is vital for RXC detectors because it can protect them from being damaged during the DSM baking phase when the temperature reaches $240 (\pm 10)^\circ\text{C}$. Helium is used as a cooling medium in this cooling circle owing to its low activation and good heat exchange with copper. To increase the gas resistance and expand the heat transfer area, a labyrinth structure is introduced into the internal structural design of a heat exchanger. In this paper, an analysis of the heat load of the RXC and its cooling circle is presented, along with the thermal simulation and test results. Thermal simulation results indicate that the cooling circle design can meet the requirements. A test platform is built to validate the cooling circle design. The experimental results are presented, and the problems encountered during the testing are analyzed. The test results indicate that the maximum temperature of the detector is lower than 65°C with the cooling circle during the platform baking phase, which is lower than the detector operation temperature limit of 75°C .

1. Introduction

The ITER radial X-ray camera (RXC) was designed to measure the poloidal profile of soft X-ray emissions from plasma, which is an important diagnostic system in the tokamak system. It is used to provide measurements of the low (m, n) magnetohydrodynamic modes, saw teeth, disruption precursors, H-mode, edge-localized modes, and L-H transition [1–3]. To achieve a whole view of the plasma and prevent the detectors from a neutron flux, an RXC is installed in the middle of the diagnostics shielding module (DSM) of equatorial port plug 12 [4,5]. The internal camera is installed in the vacuum camera tube, whereas the external camera is installed under secondary vacuum pressure. The detector array (Series 5T of Centronic Ltd., Craydon, United Kingdom) is used to detect X-rays in the RXC, which has 35 channel positive-intrinsic negative (PIN) photodiodes and can offer high blue sensitivity coupled with a high shunt resistance and low dark leakage current [6].

The DSM temperature will be higher than the detector limit temperature of 75°C during the normal operation phase, and will be $240 (\pm 10)^\circ\text{C}$ during the baking phase. As a result, the detector array will be broken because the internal camera tube is fixed on the DSM. To protect the detector array from high temperature, a cooling circle is adopted. The ambient temperature of the internal camera is higher worse than that of the external camera, and thus, the cooling circle

design of the internal camera is more important. Considering the feasibility and economic benefit, the cooling circle design mainly focuses on the cooling of the detector.

The remainder of this paper is organized as follows: Section 2 describes the structure of the RXC and its cooling circle, a thermal analysis of the RXC, and the cooling circle. The results of a thermal simulation are provided in Section 3. In section part, the temperature distribution simulated with ANSYS is also described, including the temperature distribution of the cooling circle and ceramic socket. Section 4 shows the test platform and test results. Finally, some concluding remarks are given in Section 5.

2. Thermal analysis of cooling circle

The structural design of a RXC cooling circle is presented in this section. The cooling circle is composed of a heat exchanger and a cooling pipe. The cooling pipe consists of an intake pipe, an exhaust pipe, and a branch pipe. The detector and its ceramic socket are the components to be cooled. To validate the feasibility of the cooling circle design, the heat transfer of the RXC and its cooling circle are analyzed. An approximate analysis of the heat load of the RXC, and the main factor contributing to the temperature increase of the detector, can be derived, which is meaningful to the structural design of an RXC within a

* Corresponding author.

E-mail address: chenyebin@ipp.ac.cn (Y. Chen).

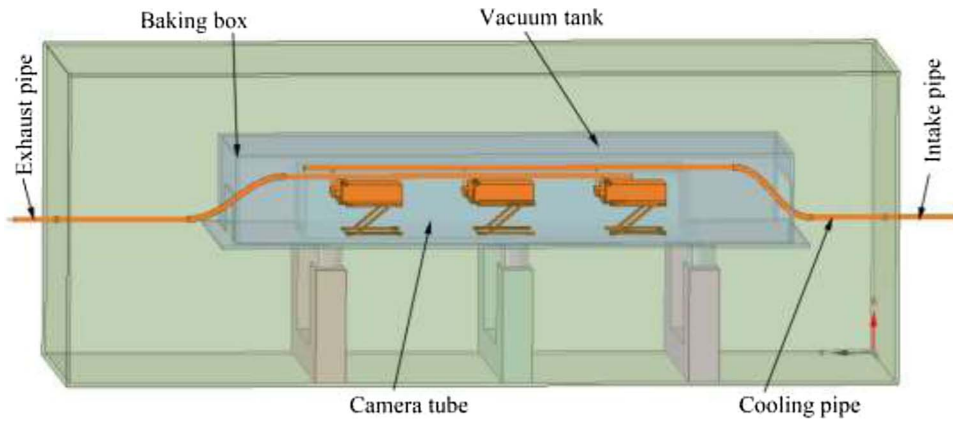


Fig. 1. Structure of heating and cooling circle.

limited space.

2.1. Structure of cooling circle

The structure of the heating and cooling circle designed for simulation and testing is shown in Fig. 1. A vacuum tank is used to form a vacuum environment. A baking box with a heating cable mounted on the surface is installed in the vacuum tank, and a camera tube is fixed to the bottom of baking box. The intake and exhaust pipe exit the vacuum tank through a closure flange. As shown in Fig. 2, the cooling gas in the circle flows into three heat exchangers through a separated branch pipe.

The detector housing (shown in Fig. 3) installed in the internal camera tube is an important part of an RXC camera [7–9], which is used to protect the detector and construct the light path of the X-ray. The detector housing was machined using 316L stainless steel, the surface of which is polished to improve the heat reflection. Four stainless-steel Z stents (shown in Fig. 3) were designed to reduce the thermal conduction from the internal camera tube, and were used to fix the detector housing to the camera tube. A heat exchanger is fixed on the detector housing using four thin stainless-steel legs (shown in Fig. 3) to reduce the conduction heat that transfers from the detector housing. To expand the thermal contact area, a labyrinth structure (shown in Fig. 4) is introduced into the internal structure of the heat exchanger. The ceramic socket (shown in Fig. 5), tightly fixed on the heat exchanger, is installed in the detector housing, which is not connected with other objects, and can be cooled through the heat exchanger.

2.2. Heat transfer analysis and calculation

To validate the structural design described above, the heat load of the RXC and its cooling circle is analyzed. Two factors contribute to the temperature rise of the detector housing: one is thermal radiation from

the internal camera tube, and the other is thermal conduction from the Z stents fixed to the internal camera tube. Heat absorbed by the detector comes from the following aspects: radiation heat from the inner surface of the detector housing, and conduction heat from the ceramic socket. To reduce the absorption of radiation heat, the surface of the detector housing and cooling pipes should be polished and wrapped with a thermal insulation material. Multi-layer insulation (MLI) [10] with an emissivity of $0.028 \text{ W}/(\text{m}^2 \text{ K}^4)$ is used to wrap the detector housing and cooling pipe, with the exception of branch pipes owing to their irregular structure. Because the vacuum pressure in the internal camera tube is 10^{-4} Pa , the thermal convection can be omitted. In the following parts, the thermal radiation and thermal conduction of the RXC and its cooling circle are mainly discussed.

2.2.1. Thermal radiation analysis

Radiation heat is an important factor contributing to the temperature rise of a detector and the cooling circle. There are two thermal radiation sources, one is the inner surface of the detector housing, and the other is the camera tube. The ceramic sockets mainly receive radiation heat from the inner surface of the detector housing, and the cooling circle mainly receives radiation heat from the camera tube. The flow rate of radiation heat [11] between the radiation source and receiver can be calculated as

$$\frac{Q_1}{\Delta t} = UA\Delta T, \quad (1)$$

where U is the heat transfer coefficient, $Q_1/\Delta t$ is the heat flow rate, ΔT is the temperature difference, and A is the area.

Theoretically, the heat transfer coefficient [12] between two objects with emissivities ε_1 and ε_2 , under a vacuum, is

$$U = 4\sigma T^3 / \left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 \right), \quad (2)$$

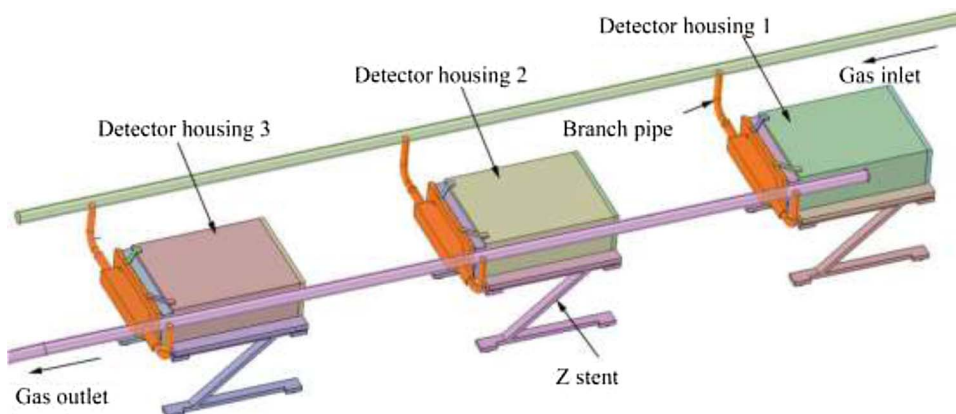


Fig. 2. Structure of closed cooling circle.

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