STRUCTURE DESIGN OF POLOIDAL HORSESHOE LIMITER FOR PULSE OPERATION HEAT LOAD IN JA DEMO

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We have developed poloidal horseshoe limiter in JA DEMO to protect the breeding blanket from the high surface heat load during the plasma operation. By evaluating the heat load on the component, which includes both surface heat load and nuclear heating, we have addressed design challenges. Our design studies, which included parametric analysis of the surface shape and considerations for the cooling circuit and component structure, have effectively resolved these challenges. This series of studies provides valuable guidelines for the design of plasma-facing components in fusion reactors.

1. INTRODUCTION

The surface of the limiter protrudes from the first wall (FW) towards the plasma which prevents heat load to the blanket. During normal operation, the limiter is responsible for suppressing the heat flux on the blanket, keeping it below an acceptable level. The abrupt events, such as vertical displacement event (VDE) and plasma disruption, make the plasma unstable, which can result in the termination of plasma current or cause the plasma to hit the FW with a large amount of stored energy. In these events, the limiter is expected to prevent a catastrophic loss-of-coolant accident in the blanket caused by the impact of runaway electrons and direct plasma contact on the toroidal circumference of the FW [1]. This conclusion is derived from the significant difference in coolant capacity between the limiter and the blanket. In the worst-case scenario, the extremely high heat load could melt the plasma-facing side of the component, causing the coolant to blast into the vacuum vessel (VV). However, the significantly reduced coolant volume in the limiter, compared to the blanket, minimizes coolant leakage, thereby substantially mitigating the risk of VV breakage and ensuring the containment of the radioactive product.

The conceptual design for JA DEMO has been studied and developed [2], and the poloidal horseshoe limiter concept was proposed for JA DEMO [3]. The limiter continues in the poloidal direction, except in the divertor area, and is discretized in toroidal direction at 90-degree intervals. The plasma-facing surface is curved in the toroidal direction, and a tungsten mono-block (W-MB) is used as plasma-facing unit. The heat sink for the W-MB is made from reduced activation ferritic/martensite(RAFM) steel, specifically the F82H pipe. Additionally, 15.5 MPa pressurized water is adopted as the coolant, in line with the heat sink material. The objective of this paper is to refine the limiter design from both thermal and structural perspectives, specifically addressing the heat load during the planed pulse operation in JA DEMO.

2. EVALUATION OF SURFACE HEAT LOAD DEPOSITED ON THE LIMITER

The surface heat load includes the charged particle heat load, radiative heat load, charge-exchange neutral particle heat load, and ripple loss alpha particle heat load. The charged particle heat load is transferred from the core plasma to the FW along the magnetic field lines. The primary concern regarding the charged particle heat load arises from the fact that the incident angle at which the magnetic field lines intersect the FW can lead to localized high heat flux. The charged particle heat load on the limiter is evaluated through three-dimensional magnetic field tracing, and the limiter surface shape required to support the cooling capability of the W-MB has been determined to have a protrusion height of 30 mm and a protrusion width of 300 mm [4]. Regarding the limiter occupying the FW area instead of blanket for tritium breeding, the limiter accounts for 2.4% of the FW, which has a limited impact.

An investigation was conducted to assess the possibility of overheating on plasma-facing side by means of evaluating the transient charged particle heat load during the planned pulse operation in JA DEMO [5]. Fig. 1 shows the transient plasma shape during plasma current ramp-up/down, as well as the distribution of the charged particle heat load on the inboard side limiter surface at specific time slice during the pulse operation. The maximum heat flux from the charged particle heat load during the operation is estimated to be 2.8 MW/m^2 at the last second of the limiter configuration plasma. Since this heat flux is well below the W-MB's estimated cooling capability of 4.1 MW/m^2 [3], the limiter design is considered acceptable in terms of surface heat load.

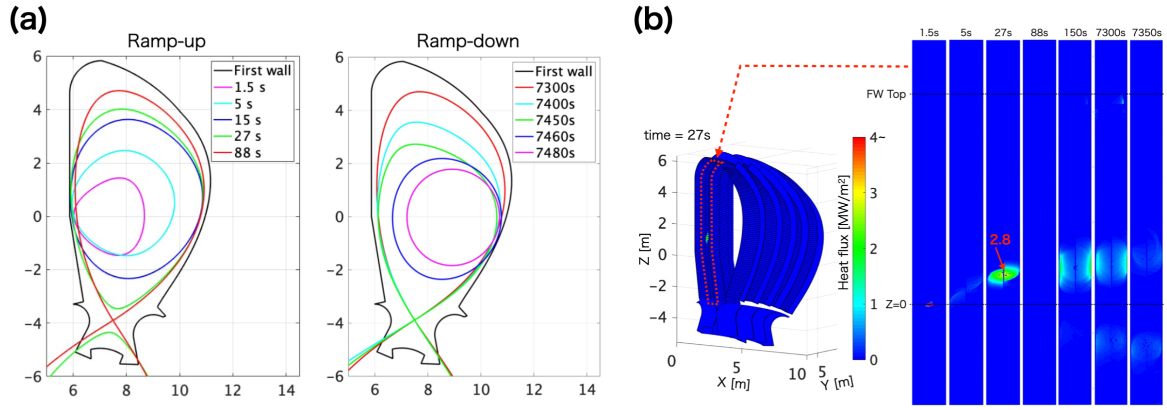

Fig. 1 Transient charged particle heat load on the inboard limiter with (a) change of plasma shape during ramp-up/down and (b) heat flux distribution.

3. STRUCTURAL DESIGN OF THE LIMITER

In the structural design of the limiter, nuclear heating must be considered alongside surface heat load, as it affects the cooling requirements. The concept of the limiter structure is shown in Fig. 2 [4]. The limiter is divided into inboard and outboard sections, in accordance with the in-vessel components' remote maintenance strategy [6]. The inboard and outboard limiters are cooled separately. The plasma-facing side of the limiters is divided into several modules, which receive coolant from the rear limiter cassette. These modules connect to the main line inside the limiter cassette in a parallel configuration. The amount of heat that can be cooled from the limiter is proportional to the number of modules, due to the total mass flow of the coolant. Based on the simulated nuclear heating and the balance between heating and cooling, the numbers of the limiter modules has been evaluated as eight for the outboard and seven for the inboard.

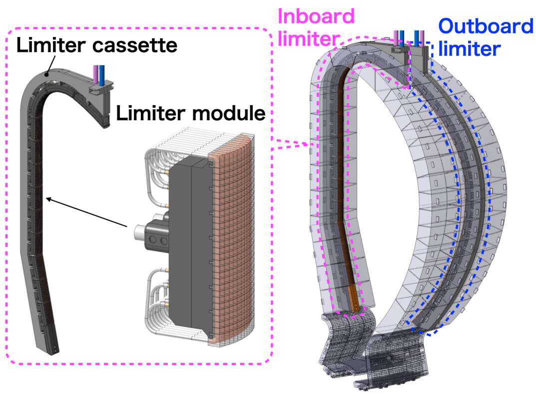

Fig. 2. Concept of limiter structure

Based on the designed concept, the thermal stress of the limiter structure was investigated, with a particular focus on the plasma-facing unit due to its importance. High stress was observed at the inner surface of the F82H pipe in the W-MB using the finite element method (FEM) simulation. The high stress is believed to result from the difference in the thermal expansion coefficients of the materials. A search was conducted for an appropriate material to serve as an interlayer between tungsten and the F82H pipe. By considering the coefficient of thermal expansion and materials compatibility, titanium was identified as a prospective candidate for this purpose [7]. The material substitution simulation demonstrated a 40% reduction in stress at the inner surface of the F82H pipe, indicating a significant decrease in stress levels compared to the original design. This design modification successfully resolves the structural challenge.

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