Numerical Study of High Heat Flux Performances of Flat-Tile Divertor Mock-ups with Hypervapotron Cooling Concept

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Abstract The hypervapotron (HV), as an enhanced heat transfer technique, will be used for ITER divertor components in the dome region as well as the enhanced heat flux first wall panels. W-Cu brazing technology has been developed at SWIP (Southwestern Institute of Physics), and one W/CuCrZr/316LN component of 450 mm×52 mm×166 mm with HV cooling channels will be fabricated for high heat flux (HHF) tests. Before that a relevant analysis was carried out to optimize the structure of divertor component elements. ANSYS-CFX was used in CFD analysis and ABAQUS was adopted for thermal-mechanical calculations. Commercial code FE-SAFE was adopted to compute the fatigue life of the component. The tile size, thickness of tungsten tiles and the slit width among tungsten tiles were optimized and its HHF performances under International Thermonuclear Experimental Reactor (ITER) loading conditions were simulated. One brand new tokamak HL-2M with advanced divertor configuration is under construction in SWIP, where ITER-like flat-tile divertor components are adopted. This optimized design is expected to supply valuable data for HL-2M tokamak.

Keywords: divertor components, hypervapotron cooling channels, heat transfer, fatigue life
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1 Introduction

The divertor is one of the key components of ITER. Generally its main function is to extract heat, helium ash and other impurities from the core plasma. Compared with the first wall, the divertor component will face much more extreme challenges, such as steady heat flux ranging from 5 MW/m\(^2\) to 20 MW/m\(^2\). Besides activated cooling with high temperature and high pressure water, a heat transfer enhancement technique is also required to achieve a sufficient margin below the critical heat flux at a reasonable water flow velocity. The hypervapotron (HV) and swirl tube (ST) are the two main heat transfer enhancement methods for divertor dome and vertical targets, respectively [1]. In fact, the HV concept was once envisaged for the plasma facing components at the vertical targets of the ITER divertor. However, it was finally abandoned on account of the postulated occurrence of a “cascade tile failure” effect [2]. Fortunately, flat tile mock-ups with HV channels intended for the ITER divertor dome have been shown to accommodate those specifications required by ITER [3]. Moreover, the ITER dome Qualification Prototypes (QP) with a HV cooling tube have successfully passed the specified thermal fatigue cycles in Russia [4].

Due to its unique characteristics (such as low activation, low sputtering erosion, high strength and reasonable thermal conductivity) [5], tungsten (W) is considered to be the divertor armor material [6]. As there is a mismatch in thermal expansion and elastic modulus between W and CuCrZr heat sink, the interface, where only a reasonable temperature gradient appears, still suffers high stress. Therefore, it is necessary to assess whether the thermal stress will exceed the critical criteria of the materials.

By using a brazing technology [7], a W/CuCrZr/316-LN divertor component element of 450 mm×52 mm \times 166 mm with HV cooling channels will be manufactured at Southwestern Institute of Physics (SWIP); and then it will be tested in the newly constructed SWIP 60 kW Electron-beam Material testing Scenario (EMS-60) [8,9]. In order to optimize the structure of divertor component elements, ANSYS-CFX used in CFD analysis and ABAQUS aiming for thermal-mechanical calculations were performed together. Both codes were utilized to select reasonable thickness of tungsten tiles (\(T\)), width of slits among tiles (\(W_d\)) and the W tile size.

When the mock-up is exposed to repeated thermal loads, even if the stress values may never exceed the
ultimate tensile strength of materials at each cycle, it could still get cracked and fail. This fatigue failure process of the loaded component consists of three stages: crack initiation, crack propagation and final failure. The software FE-SAFE is used to establish the numerical model to assess the first stage that also determines the thermal fatigue performance.

A flow chart specifying the overall simulation process is shown in Fig. 1, which can be outlined in four consecutive steps. Firstly, CFD analysis was done by ANSYS-CFX, and it outputted heat transfer coefficient (HTC) data of the cooling tube to perform thermal-mechanical analysis by ABAQUS. At the second stage, temperature distributions from steps 1 and 2 could be contrasted. Next, thermal-stress analysis was carried out to obtain stresses and strain values, serving as important inputs for the last stage—fatigue analysis.

A new tokamak machine HL-2M with advanced divertor configurations, such as snowflake and tripod, is under construction in SWIP. It is estimated that the heat load on the target plates can be arranged from 3 MW/m² to 7 MW/m² depending on different divertor configurations. In order to meet the operation requirements of HL-2M, an actively-cooled ITER-like flat-tile design of divertor is adopted. The work in this paper will supply valuable data for HL-2M tokamak divertor target plates design.

2 Computational modeling

2.1 3D Analysis model

The 3D model of a divertor component element with dimensions of 450 mm (length) × 52 mm (width) ×166 mm (height) is shown in Fig. 2. This model consists of three sections: (1) W tiles as plasma facing material (PFM), (2) CuCrZr heat sink with HV cooling channels and (3) 316-LN as the structural material. To evaluate the size effect of W tiles, three different tile sizes were considered, including 50×50 mm² (full size), 25×25 mm² (1/4 size), and 12.5×12.5 mm² (1/16 size). To simulate the real load conditions of the components under ITER operation scenario, the nuclear heating load used in numerical simulation (shown in Fig. 3), required the mockup to be exposed to a complex heat flux: a steady state heat flux of 5 MW/m² for 328 s plus a pulse heat of 10 MW/m² for 12 s. This study only calculated one cycle (i.e. 400 s) for saving computational time. All materials were assumed to be elastically isotropic, and temperature-dependent physical properties (density, thermal conductivity, mean thermal expansion, thermal conductivity, Poisson’s ratio, Young’s modulus) were acquired from the ITER material handbook.

A commercial CFD code, ANSYS-CFX, was adopted to analyze the flow characteristics. Due to the deficiency of the code in computing incomplete boiling, the phase change is not considered. The flow field is assumed to be turbulent. The governing equations for the continuity, momentum, turbulent kinetic energy, and turbulent kinetic energy dissipation are described in Ref. [12].

The software ANSYS ICEM-CFD was used to generate the mesh. Regular tetrahedron meshes were employed in the solid body, while mixed tetrahedral and prism meshes were used in the fluid zone for good computing accuracy in the boundary layer. The total number of meshes was about 3 million as shown in Fig. 4.

Fig.4 Finite element mesh of the model. (a) Cross-section, (b) HV cooling tube
In order to make a comparison with the experimental results, the inlet temperature of 20 °C and the outlet pressure of 10 bars based on the cooling condition of EMS-60 were adopted for the calculation, while the inlet water velocity \( V_{in} \) could be changed from 4 m/s to 10 m/s. CFD analysis was used for observing the impact of different coolant boundaries on heat transfer under different heat flux, while the tiles’ thickness (7 mm) and slits’ width (1 mm) could be set as constants. The top surface was exposed to the heat load as illustrated in Fig. 3, and other surfaces of the component exposed to vacuum environment could be regarded as adiabatic walls since a very small proportion of heat is transferred through these boundaries.

### 2.3 Thermal-stress and fatigue analysis

The HTC statistics of different cooling boundaries needed in transient thermal analysis by ABAQUS were obtained from CFD analysis. Thus thermal analyses not only by ANSYS-CFD but also by ABAQUS can be available and the temperature distributions are compared, as shown in Fig. 5(a).

Calculation of stress was based on the worst cooling condition \( V_{in} \) of 4 m/s. The studied variables include: \( T \) (5 mm, 7 mm and 10 mm), \( W_d \) (0.5 mm and 1 mm) and the tile’s dimension (full, 1/4 and 1/16). For simplification, only a part of the mock-up exactly armored with three types of tiles was analyzed. Temperature distributions obtained during thermal analysis served as the heat load. The constraints consisted of the bonds used at the interfaces of W/CuCuZr and Cu-CrZr/316LN, and the zero displacement at the vertical direction of the bottom.

Depending on the stress values, fatigue can be divided into stress fatigue and strain fatigue. If the maximum stress is beyond the yield strength of the material, plastic strain occurs, and the mockup may fail under low-cycle fatigue. In that case, it is better to use the strain rather than the stress as the fatigue failure control factor. In the ITER divertor environment, the stresses are usually above the yield strength of materials, and thus strains are applied in the following fatigue analysis.

The calculation of fatigue life used a relationship between amplitude strain \( \varepsilon \) and the number of cycles \( N \) to failure of tungsten at room temperature \([13]\).

\[
\varepsilon_{total} = [0.774 \times (N_f)^{-0.0536}] + [0.25 \times (N_f)^{-0.3}]. \tag{1}
\]

The strain field at notches of the structure was estimated during the stress analysis. The value of damage \((1/N_f)\) at certain strain could be solved from Eq. (1). The fatigue analysis which was based on linear damage cumulative rules, incorporating a maximum strain-morrow algorithm, enabled us to estimate the fatigue life \([14]\).

### 3 Results and discussion

#### 3.1 Temperature distribution

The temperature changes of Pt1 and Pt2 (shown in Fig. 2) by CFD at \( V_{in} \) of 4 m/s are given in Fig. 5(a). Both of them have nearly achieved equilibrium after 10 s at 10 MW/m², indicating a good thermal conduction of the component. The maximum temperature of Pt1 (Max.Pt1) was 962 °C, which was much lower than the recrystalization temperature of pure W (1250 °C) \([15]\). The maximum temperature of Pt2 was only 408 °C, and then physical and mechanical properties of CuCrZr alloy could be maintained \([16]\).

The Max.Pt1 dependent on both \( V_{in} \) and heat flux was specified in Fig. 5(b) in which the CFD results are compared with values calculated by ABAQUS. Max.Pt1 decreased much more evidently when \( V_{in} \) increased from 4 m/s to 6 m/s, and further increase of \( V_{in} \) did not significantly improve heat transfer ability when it was larger than 6 m/s. The match of calculated results between CFD and ABAQUS was good when the inlet water velocity was above 6 m/s. But the deviation was evident at the \( V_{in} \) of 4 m/s. It could be explained by two reasons: the algorithm difference of these two codes; errors of HTC during the transferring process—with lower \( V_{in} \), HTC had a bigger influence on heat transfer, and then its errors caused much more apparent deviations.

#### 3.2 Stress and fatigue life analysis

As the material properties of the 80 μm brazing layer are not known \([7]\), the brazing layer cannot be taken
into account in the analysis, where the calculated stresses at the W/Cu interface would be extremely large. For the purpose of understanding the stresses much more accurately, the plane of 0.5 mm above the W/Cu interface was cut to plot the stress distribution (Fig. 6).

Thermal stress distribution for the base concept \([T (7 \text{ mm}) \text{ and } W_d (1 \text{ mm})]\) during the whole period is shown in Fig. 6(a). Stresses reached the peak at 212 s, namely the end of pulse heating, where the maximum stress appeared at the edge corner of the full size tile; as tile size was reduced, the corresponding stress decayed.

Stress contrasts of four concepts (concept 1: \(T (5 \text{ mm}) \text{ and } W_d (1 \text{ mm})\), concept 2: \(T (10 \text{ mm}) \text{ and } W_d (1 \text{ mm})\), concept 3: \(T (7 \text{ mm}) \text{ and } W_d (0.5 \text{ mm})\) and the base concept) are shown in Fig. 6(b). Comparing concepts 1, 2 with the base concept, with the same \(W_d\) of 1 mm, stress increased sharply when \(T\) was over 7 mm. Thus the thickness of 10 mm should be eliminated to reduce stress.

Comparing concept 3 with the base concept, with the same \(T\) of 7 mm, the drop of slits width did not have too much effect in decreasing the stress. Referring to ITER first wall design \cite{17}, 1 mm could be an appropriate selection.

The fatigue life of mockups for three concepts is shown in Fig. 7. In each concept, the lowest fatigue life occurred at the interface of the full size W tile and heat sink where the maximum stress existed. Taking the issues of stress and fatigue life into consideration, the full size tile could be excluded.

![Fig.6](a) Thermal-stress distribution of the base concept during the whole period, (b) Stress contrast of four concepts

![Fig.7](a) Fatigue life distribution. (a) concept 1: \(T (5 \text{ mm}), W_d (1 \text{ mm})\), (b) the base concept: \(T (7 \text{ mm}), W_d (1 \text{ mm})\), (c) concept 2: \(T (10 \text{ mm}), W_d (1 \text{ mm})\) and (d) the base concept with the brazing interlayer
With the thickness of 5 mm, 7 mm, and 10 mm, fatigue life was respectively 7637, 6230, 4158 cycles. Naturally, the thickness of 10 mm should be abandoned for the reason of considerably short lifetime. If we only pursue much longer fatigue life, 5 mm could be the best option. However, with thinner W tile, the heat sink CuCrZr alloy is more likely to be working at a high temperature above 475 °C, in that case its physical and mechanical properties decayed sharply. In addition, even if the thickness decreased from 7 mm to 5 mm, the fatigue life did not extend too much. Furthermore, considering the erosion of armor material during tokamak operation, 7 mm could be an appropriate selection for the thickness of W tiles.

It should be noticed that the calculation of fatigue life has ignored an intermediate layer. Actually, an intermediate layer always exists in the present study, no matter which technology is used, pure copper casting, gradient interface or direct brazing etc. Here, it is difficult to simulate the real case owing to the lack of specific material properties of the brazing interlayer, while an estimation based on approximated data is also valuable. The best source of filler material characteristics at different temperatures is experimental tests of smooth specimens. However, the technically advanced experiments are expensive and complicated. Usually, the properties of alloy could be fitted according to those of the composite elements, yet the required data of Cu and Mn are also insufficient. Finally, further analysis has no alternative but to rely on some proper assumptions, one of which is that the characteristics of filler metal are the average of those of W and Cu alloy. Based on this assumption, the fatigue life of the mockup, equipped with a filler interlayer, having W tiles of 7 mm thickness and 1 mm slits width, was computed again. Thanks to the addition of an 80 μm interlayer, the fatigue life climbed from 6230 to 16010 cycles (Fig. 7), which clearly meets the requirements of divertor life cycles by ITER. To some extent, it also verifies the scientificity of the flat-tile concept in terms of ITER operational life.

4 Conclusions

Increasing the inlet fluid coolant velocity to improve the heat transfer capability is much more effective when $V_{in}$ is lower than 8 m/s. Temperature distributions obtained by ANSYS-CFX and ABAQUS were compared. The stresses were maximized at the tile corners and they continuously declined with decreasing tile size. The fatigue life of the mock-up with different tile thicknesses was calculated as a supplement to determine the final design. Based on one approximated assumption, the fatigue life distribution of the base concept was repainted, where the added interlayer made the fatigue life soar from 6230 to 16010 cycles, which clearly meets the requirements of divertor life cycles by ITER. Certainly, this predicted result cannot show the real fatigue life but suggests a truth that the interlayer could significantly ameliorate the joining performance. Also the construction of a database of filler metal in SWIP enables us to make more accurate analysis in the future.

Overall, CFD analysis, thermal-stress calculation and fatigue analysis have been studied in succession, and it was suggested to use W tiles smaller than (50 mm×50 mm) with 7 mm thickness and 1 mm slits’ width to manufacture the mockup. HHP test results will be adopted to optimize the design.

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