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Numerical optimization of tungsten monoblock tile in EAST divertor

Xiahua Chen[a,b], Fang Ding[b,*], Hongmin Mao[b], Guangnan Luo[b], Zhenhua Hu[b], Feng Xu[b], Guojian Niu[b]

[a] *Harbin Engineering University, Harbin 150001, China*
[b] *Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China*

HIGHLIGHTS

- A method based on Kriging model and Uniform Design is developed and applied to the geometry optimization of EAST W tile.
- An optimized chamfering geometry is obtained and significantly reduces the maximum temperature on W monoblock.
- The incident angle of plasma flux has a strong impact on the optimized chamfering geometry.

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ABSTRACT

The ITER-like tungsten divertor with toroidally symmetric 1 mm × 1 mm chamfers on monoblock tiles has been installed in EAST in 2014. Hot spots were experimentally observed mostly along the toridial facing gaps between two columns of W/Cu monoblock units, which are often aggravated by installation misalignment. These hot spots can significantly degrade the power handling capability of W divertor and need to be alleviated.

A numerical optimization model for tile chamfering design is built based on the finite element method (FEM), in which the numerical experiments are designed by the uniform table. The calculation results in ANSYS for these experiments are then processed employing the code Design and Analysis of Computer Experiments (DACE) in which the Kriging method is adopted to reconstruct a response surface. The optimum geometry can be derived from the minimum point on the surface. The results show that, under 200 MW/m^2 parallel heat flux with an inclination angle of 3° with respect to tile surface, the maximum temperature on W tile with a 0.5 mm misalignment can be decreased to 2084 °C by adopting an optimized single-sided chamfer, 1.8 times lower than 1 mm × 1 mm symmetrically chamfered tile. The optimum chamfering geometry has a strong dependence on the inclination angle of plasma flux to tile surface. As a result, the monoblock tiles in a flat cassette module need to be chamfered differently to adapt to the varied inclination angles.

1. Introduction

The plasma interaction with plasma-facing components (PFCs) in tokamaks is a subject of intensive research, especially because of implications for ITER and future fusion reactors. Although isolated from the plasma core, the PFCs can significantly restrain the operational regimes of fusion machines. An important limitation is the heat flux coming from the plasma onto the PFCs [1] which must not exceed the material limits (around 10 MWm^{-2}), otherwise cracking and melting of the tiles will occur. In steady state, high heat flux divertors, the PFCs have to be castellated—i.e. split into small blocks separated by gaps, in order to withstand stresses caused by plasma heat loads and induced currents. Besides the positive effects like reduced risk of cracking, the castellation will lead to the increased probability of melting of the castellated PFCs due to local power loads on leading edge of the gaps.

Tungsten (W), owing to its high melting point, low sputtering yield, high thermal conductivity and low tritium retention [2], is among the main candidate-PFCs for a fusion reactor and will be exclusively used in the ITER divertor from the beginning of operation [3]. Melting is one of the major risks associated with the material and PFCs in tokamaks like JET or ITER are designed with surface shaping [1,4]. In 2014, EAST upgraded its upper divertor into W-PFC with ITER-like actively-cooled monoblock

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[*] Corresponding author at: 350 Shushanhu Road, P.O. Box 1126, Hefei, Anhui 230031, China.
E-mail address: fding@ipp.ac.cn (F. Ding).

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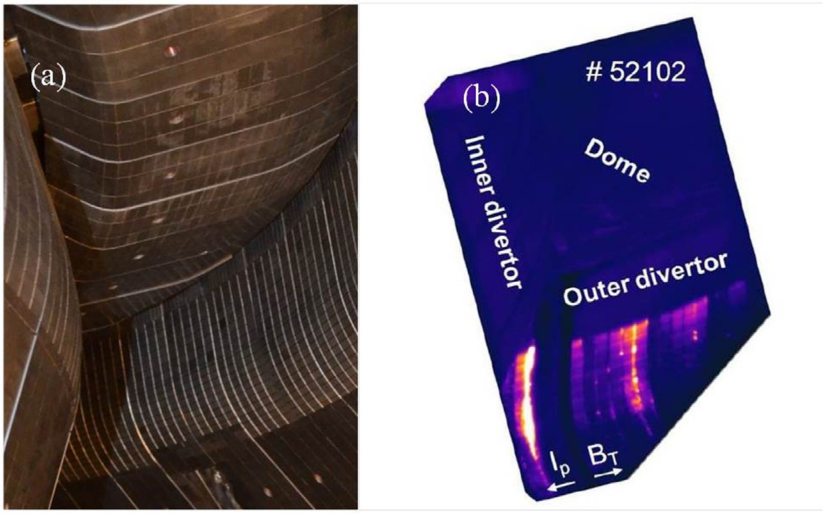

Fig. 1. (a) The upper W divertor of EAST. (b) An infrared image of the W divertor in shot 52102.

W/Cu-PFC comprising 80 cassette modules. Every divertor cassette module is composed of compact-sized monoblock tiles with dual 1 mm × 1 mm chamfering in toroidal direction (Fig. 1(a)). Fig. 1(b) exhibits an infrared image of W divertor in shot 52102. Hot spots were found mostly located at tile edges in the toroidal facing direction, which could cause impurity ejection from the tile surface [5], even damage the PFCs. In order to alleviate this risk, simulation analyses are carried out to optimize the design of surface geometry in this paper. New chamfering geometries for monoblock tile are proposed to avoid the leading edges directly exposed to plasma and reduce the maximum temperature on W tiles significantly.

2. Modeling

The thermal load is one of the most important factors to decide the shape of the tile [6–8]. The simulation calculations in this work are taken with regard to thermal analysis under supposed heat flux.

2.1. Geometry parameter and finite element model

The infrared image in Fig. 1(b) shows that the hot spots mostly appear at toroidal facing edges. So a two-dimensional model is developed, in which the leading edge effects in poloidal facing side are neglected.

Fig. 2 shows the configuration of the tile with respect to deuterium plasma flux [9]. The armour material of tile is tungsten. The coolant tube which made of CuCrZr alloy is inserted into the interior of the tile. CuCrZr alloy is a kind of heat sink material with good mechanical strength to disperse the heat flux towards the coolant. An 1 mm thick pure copper interlayer is used between the tungsten armour and the CuCrZr heat sink to reduce the thermal stress caused by the mismatch of thermal expansion between the two different materials. The heat flux transferred through the CuCrZr tube (Φ12 mm × 1.5 mm) is taken away through forced convection heat transfer. The chamfering geometry is chosen considering its simplicity in calculation and machining. The four controlling dimensions in chamfering structure, X1, Y1, X2, Y2 as shown in Fig. 2, are set as the design variables in the model.

Finite element model can be generated by commercial software ANSYS 14.0 in which the two-dimensional element PLANE77 is used for thermal analysis. Finite element mesh is generated in a free type since it's hard to get a unified strategy to mesh structured grid for different tile shapes. The mesh size is 0.2 mm. The physical property parameters such as thermal conductivity of material are taken from *ITER material handbook* and they are temperature dependent.

2.2. Boundary condition

In this model, the thermal analysis is taken under a steady state heat flux loading, which is a normal method in other researches for the PFC design [10]. The transient thermal shocks, e.g. ELMs, have a major influence on surface morphology and composition and need to be processed in other modes, which is beyond the scope of this paper and will not be considered here. The tiles are heated by plasma flux along the magnet field line. The cosine law can be applied, namely, the vertical component of heat flux to tile surface is taken as the thermal load for finite element model. That has been verified in other experiments [11]. 3° is set as the plasma incident angle θ (Fig. 2) with respect to W tile surface in the model based on experimental data. The perpendicular peak heat flux incident on the W/Cu monoblock structure has to be limited to 10 MW/m^2 [12] which is the maximum thermal transfer capability of current divertor design. That means the corresponding the highest parallel heat flux should be around 200 MW/m^2. The gap width between neighboring tiles is 0.5 mm. The maximum installation misalignment allowed is 0.5 mm for adjacent tiles. The geometry shielding effect by the adjacent tile is considered in simulation.

The forced convection effect by water flow is applied on the inner surface of CuCrZr tube as boundary condition. The heat transfer coefficient h can be derived from the Dittus-Boelter empirical correlation [13]:

$$h = 0.023\frac{\lambda}{d}\left(\frac{dv\rho}{\mu}\right)^{0.8}\left(\frac{c_p\mu}{\lambda}\right)^{0.4} \quad ,(1)$$

where d is the hydraulic diameter (12 mm), λ is the thermal conductivity of water, c_p is the specific heat capacity of water, ρ is the water density, μ denotes kinetic viscosity of water, v is the average fluid velocity and 5 m/s is set here. 50 °C is set as the local water temperature. The calculation shows that varying the water temperature from 25 °C to 60 °C does not influence the optimization results, just causing about 5% error in the maximum temperature. The pressure of water coolant is 0.6 MPa. The other physical property parameters can be retrieved based on these conditions.