

Parametric investigation of temperature evolution in actively cooled plasma-facing components during high heat fluxes

O. V. Ogorodnikova, M. Roedig, J. Linke

Forschungszentrum Juelich, EURATOM-Association, 52425 Juelich, Germany

Introduction

Due to the first wall and divertor in fusion devices like tokamak are submitted to high heat fluxes, their design needs the use of actively cooled component technology. Plasma-facing components are composed of (1) a plasma-facing material (Be, W, CFC), (2) a compliant layer (Cu OFHC), (3) a copper alloy tube (CuCrZr) and (4) structure material (SS). Several design concepts have been developed like flat-tile concept or the macro-brush concept and the saddle-like monoblock [1]. To investigate the degradation of the heat transfer from the plasma-facing material to the heat sink, high heat flux (HHF) tests have been performed on mock-ups with different design. Several electron beam and particle beam facilities are involved in HHF testing of plasma-facing components. It was found that most of surface temperatures in HHF test from different machines are comparable [2]. In this paper, mock-ups have been investigated in respect to heat removal efficiency during the steady state operation. The screening test of ITER-relevant first wall and divertor mock-ups has been carry out in an electron beam facility JUDITH. Temperature distribution during the test is modeling by commercial code ANSYS.

Be mock-ups

Actively water cooled Be mock-up is representative for the ITER first wall (FW). Preliminary FW mock-up is made from a combination of beryllium flat tiles (as an armour material), a water cooled copper alloy CuCrZr (as a heat sink material) and a stainless steel SS316L (as a structure material). The Be armour material was joined onto the Cu heat sink material by hiping or brazing. In order to reduce the stresses, the Be plate was segmented into several tiles. Up to now several mock-ups were fabricated and thermal fatigue tested [3]. The temperature distribution in mock-up with 9 mm bulk Be loaded at $P=3 \text{ MW/m}^2$ is shown in Fig. 1. The hydraulic conditions used in the experiments were following: smooth tube, water speed $v=5 \text{ m/s}$ and water temperature $T=20^\circ\text{C}$. The increase of the water velocity by two times results in the reduction of the surface temperature of about 50°C (Fig. 2). The presence of SS cooling tubes in a present design significantly increases the

maximum temperature because SS has less thermal conductivity compared to Cu. The design using the Cu cooling tubes instead of SS tubes is preferable in respect to the increase of the heat transfer efficiency. The calculations describe well experimental data.

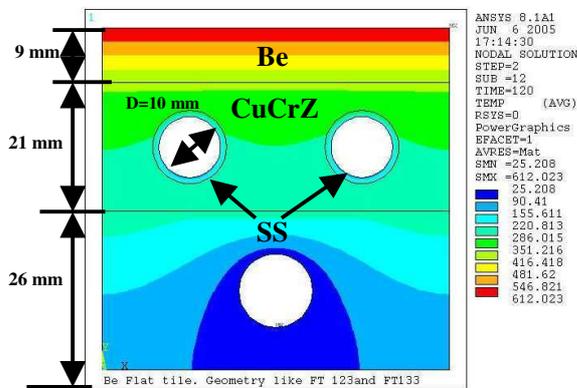


Fig. 1. Steady state temperature distribution in Be mock-up under power load of 3 MW/m².

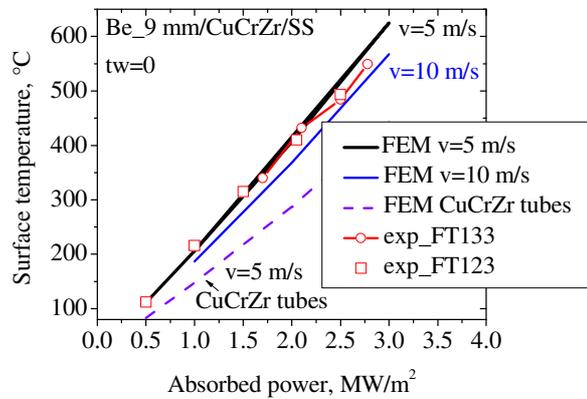


Fig. 2. Surface temperature as a function of power load.

Thermal fatigue tests show that mock-ups with Be tiles withstand a heat flux up to 2.5 MW/m² for 1000 cycles. In general, Be flat tile modules did not show the degradation of heat transfer during thermal fatigue loading. The steady state temperature remained almost constant during the cyclic loading until complete failure occurred.

An alternative option for the FW is Be coating on heat sinks. Several mock-ups consisted of a 5 mm and 10 mm plasma-spray Be (PS-Be) on heat sinks made of CuCrZr [4] have been tested. The cooling channel was equipped with a twisted tape (tw=4) as heat transfer enhancement. The steady state temperature for 10 mm Be as a function of the absorbed power is shown in Fig. 3. Cooling conditions were: water speed v=5.5 m/s and water temperature T=20°C.

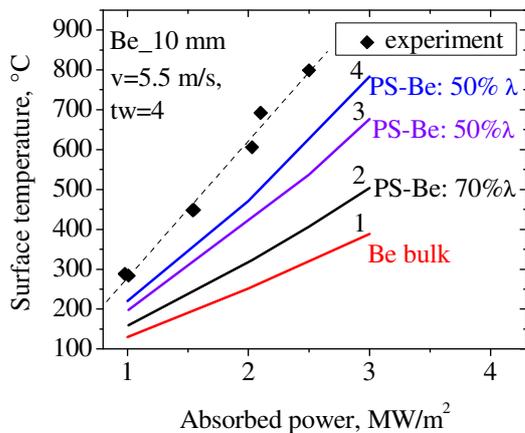


Fig. 3. Surface temperature as a function of power load. Lines 1-3 are calculations without an interlayer of Cu and Be blocks. Line 4 is a real design.

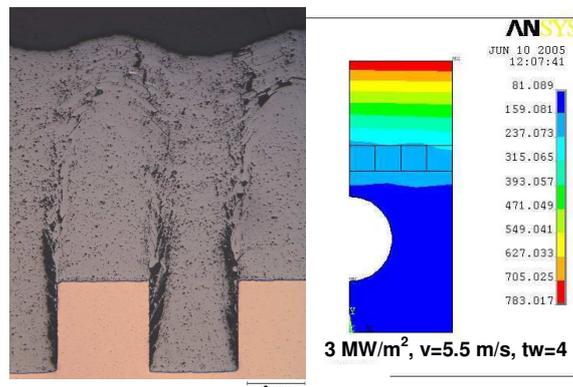


Fig. 4. a) Real design. b) Steady state temperature distribution in PS-Be mock-up under power load of 3 MW/m².

The higher is the thermal conductivity the higher is the heat removal capacity and less the surface temperature of mock-up. The thermal conductivity of PS-Be is 50% less than bulk Be that drastically increases the surface temperature of mock-ups. Additionally, PS-Be was produced in cubic Cu projections (1.5 mm for 5 mm coating and 3 mm for 10 mm coating) and, from this, there are an interlayer of Cu and Be blocks (Fig. 4a). This also results in an increase of the surface temperature of 100°C compared to a design without interlayer. The conclusion is that the bulk Be has essentially better heat removal efficiency than PS-Be.

An example of the influence of the cooling water velocity and the thickness of the plasma-facing material is shown in Fig. 5. The reduction of the Be thickness by two times results in a reduction of the peak temperature by about 1.7 times. The variation of the CuCrZr thickness of ± 2 mm results on a variation of the surface temperature of 40°C. An increase of the water speed (and water temperature) decreases the surface temperature because of the increase of the heat transfer coefficient.

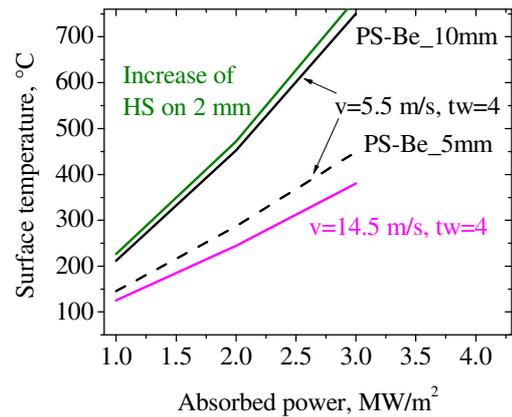


Fig. 5. Surface temperature as a function of power load for PS-Be for different thicknesses and different cooling water velocities.

W macrobrush and CFC mock-up: W(or CFC)/Cu/CuCrZr

Actively cooled W and CFC mock-ups have been proposed for the ITER divertor. A heat transfer enhancement technique is required in order to achieve sufficient heat removal efficiency and increase a critical heat flux at a reasonable flow rate [5]. Hypervapotron (HV) and swirl tube (ST) are used as enhancement methods (Figs.6-7).

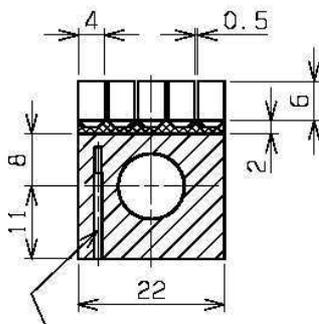


Fig. 6. Cooling by swirl tube (ST).

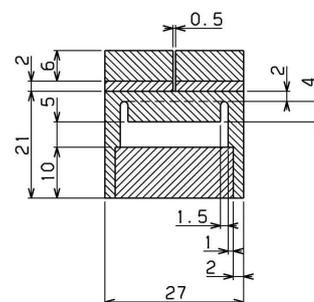


Fig. 7. Cooling by hypervapotron (HV).

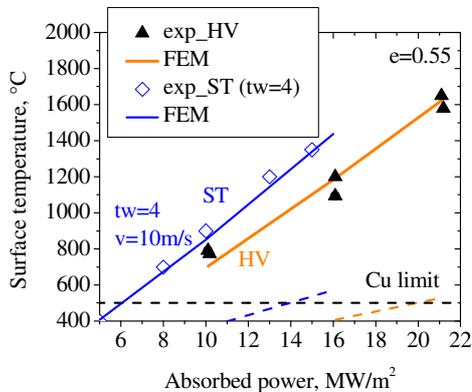


Fig. 8. Experiments and FEM for W mock-up cooling by ST and HV.

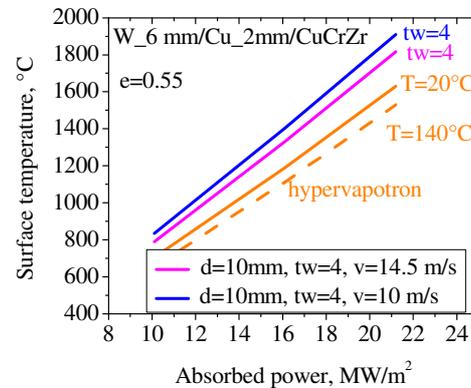


Fig. 9. Influence of cooling conditions on surface temperature of W mock-up.

The flat tile with hypervapotron (HV) cooling has the following advantages: it is cheaper and easier to fabricate than monoblock geometry. The HHF tests were performed on the W mock-ups up to 20 MW/m² and better heat removal efficiency was obtained compared to swirl tube (Fig. 8). This confirms the previous data base about good performances of HV compared with ST concept [6,7]. A comparison with FEM calculations is proposed in Fig. 8: one can check the measured temperature is in a good agreement with finite element analysis. Both the increase of the temperature and water speed decreases the peak temperature as shown in Fig. 9.

Calculations performed for the CFC components are about the same than those performed for W. The temperature of CFC mock-up is less than the temperature of W ones because of better thermal conductivity of CFC. Both W and CFC mock-ups cooling by hypervapotron have reasonable surface temperature up to absorbed power of 20 MW/m². The limitation factor could probably be the CuCrZr temperature which exceed the temperature limit of 550°C at about 20 MW/m² for HV and about 15 MW/m² for ST (Fig. 8).

Consequently, calculations describe well experiments on thermal loads and can be used for the prediction of the thermal mechanical behavior of mock-ups for future fusion devices.

References

- [1] R. Tivey, M. Akiba, D. Driemeyer, I. Mazul, M. Merola and M. Ulrickson, *Fusion Eng.&Des.*, 55 (2001) 219
- [2] M. Roedig et al., *Proc. 23rd SOFT (Venice, 2004)*, submitted to *Fusion Eng.&Des.*
- [3] K. Ioki et al., *J.Nucl. Mater.*, 329-33 (2004) 31 and ref. within
- [4] K. J. Hollis, *Plasma Sprayed Beryllium Mock Up Final Report*, FIA-02-011
- [5] A.R. Raffray et al., *Fusion Eng.&Des.*, 45 (1999) 377
- [6] F. Escourbiac, J. Schlosser, M. Merola, I. Bobin Vastra, *Fusion Eng.&Des.*, 66-68 (2003) 301
- [7] J. Sclusser et al., *Nucl. Fusion* 45 (2005) 512