WPPMI-CPR(18) 19977

G Calabro et al.

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Preprint of Paper to be submitted for publication in Proceeding of 30th Symposium on Fusion Technology (SOFT)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Preliminary investigation on W foams as protection strategy for advanced FW PFCs

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Abstract

As one among the core missions towards the realization of nuclear fusion, a future reactor must provide efficient and safe power exhaust through both divertor and first wall (FW). Recent studies have confirmed that the greatest challenges arise from the occurrence of plasma transients. Indeed, extensive damage of the plasma facing component (PFC) may occur during transients, with the risk of loss of coolant accidents (LOCA) that would hinder the safety of a future reactor as well as its prompt return to normal operation. Among the possible wall protection strategies, a sacrificial and micro-engineered surface made of porous tungsten (W) may promote the heat flux reduction while preventing the failure of the cooling pipe. As a preliminary step in this direction, the present study aims to investigate the possible application of W-based open cell foams as a sacrificial armor material. At first, an equivalent solid model, originally validated for Al open cell foams, was transferred to W foams. Then, it was decided to deal with steady state thermal FEM analysis to evaluate the equivalent thermal conductivity provided by several foam configurations. Ultimately, a scaling law of the thermal response was developed as a function of the most influential foam parameters. As a future outlook with respect to DEMO-relevant transients scenarios, the scaling law will support design optimization and tailoring of an advanced FW PFC provided with a sacrificial W foam armor.

Keywords: DEMO, plasma facing components, heat load, protection strategy, open-cell foam, FEM analysis

1. Introduction

The heat and particle exhaust inside a tokamak is currently regarded as one of the most challenging missions for nuclear fusion [1]. Divertor and first wall PFCs are subject to severe heat flux, erosion and sputtering together with additional limitations owing to the presence of a neutron flux [2]. Considering DEMO and future reactors, even harsher conditions are expected. Recent studies have disclosed that the greatest challenges arise from the occurrence of plasma transients, such as plasma limited phases, vertical displacement events (VDE) and disruptions [3]. A DEMO-like upward unmitigated VDE TQ was simulated assuming a plasma thermal energy content of 1.3 GJ and a SOL broadening factor equal to 7, in accordance with [4]. The resulting power densities onto the FW are in the order of several tens of GW/m^2 for the 4 ms of deposition time considered. As a result of these extreme heat loads, severe damage is expected due to surface vaporization, melting and re-solidification. An eventual failure of a standard FW concept [5] may result in LOCA accidents hence compromised reactor safety and delayed return to normal operation. Therefore, wall protection strategies are needed to mitigate or avoid failures. Among the many, we can mention the gas protection, including vapor shielding, recently investigated by S. Pestchanyi et al. [6]. The impinging heat flux could be lowered up to 8 – 10 times by vapor shielding. The liquid coolant protection can also be mentioned as an effective strategy, where the energy deposition is mitigated by a flowing sacrificial layer of coolant/breeder liquid.

In addition to extrinsic strategies, one may think to provide the plasma with a sacrificial layer that promotes

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the heat flux reduction by material degradation, that involves the benefits of both the above mentioned strategies. Micro-engineered structures can be tailored to allow a proper spreading of the thermal stress onto a larger volume thus preventing the failure of the cooling pipe. Although targeting inertial fusion energy (IFE) FW applications, a number of possible W-based micro-engineered armors, such as micro-machined structures, plasma-sprayed coatings, lattice structures and foams are described in [7].

Metal foams are a new class of materials with low density and novel thermo-physical properties [8]. Their market penetration is driven by the need for high performance, lightweight structures tailored for functional requirements, e.g. energy absorption, heat exchange and thermal management. However, their macroscopic behavior derives from several parameters, e.g. cell and ligament geometry, anisotropy, pore density (measured in pores per inch, ppi). An additional key parameter is the relative density $\bar{\rho}$, defined as the ratio between solid volume V_s and total volume V, but also related to foam density ρ and porosity p

$$\bar{\rho} = \frac{V_s}{V} = 1 - p \simeq \frac{\rho}{\rho_s} \tag{1}$$

Currently, very limited examples exist in literature with respect to W foams. M. Andersen et al. carried out thermo-mechanical FEM analyses on a W foam armor for IFE applications [9]. Using a 3D Kelvin cell geometry with 80×20×20 μm square sectioned ligaments, they modeled a foam with almost 10% of relative density and 100 ppi. Both steady state and transient scenarios were addressed under the same material properties and relevant loading/cooling conditions described in [7]. The foam was found a promising armor material owing to its mitigated interface mismatch, low thermal stress and enhanced helium release. This is probably due to the quasi-volumetric energy adsorption, namely the feature of spreading the load over larger areas and deeper inside the structure rather than relying only on the top surface [7], at the same time offering a shielding effect to the underlying areas. Moreover, foams admit plastic deformation, translation, twisting and rotation of ligaments, leading to relieved stress levels and hindered brittle crack propagation [8]. However, the mentioned study seemed to be affected by overestimated temperatures due to the sharp edges. In addition, only the mechanical validation was carried out, perhaps owing to technical difficulties in manufacturing and joining the foam.

With the present study, we aim to develop an equivalent and parametric model for W foams, together with a scaling law of its thermal characteristics. This would allow model calibration and design optimization, ultimately supporting the identification of promising solutions for advanced PFCs during DEMO-like transient.

2. Equivalent and parametric solid model

We relied on a model originally developed and validated by P. Fanelli et al. for Al open cell foams [10]. As shown in Figure 1, a detailed shaping of ligaments and nodes of the Kelvin cell can be tuned, starting from literature and experimental evidences, in terms of:

1. Ligament length, L
2. Ligament reference cross section area, A_0
3. Cross section profile, $f(\xi)$
4. Cell anisotropy, λ

L is a key parameter impacting pore density and relative density. This latter is also affected by the cross section area along the ligament, provided by Yang [11]

$$A(\xi) = A_0 \cdot f(\xi) = A_0(36\xi^4 + \xi^2 + 1) \tag{2}$$

where $A(\xi)$ is the cross section area at a dimensionless axial position ξ. Concerning Al foams, the peculiar manufacturing route typically leads to triangle-shaped cross section areas [11]. However, the use of circular ones in the present model does not affect the similarity [10]. The cell anisotropy, instead, is defined as the ratio between height and width of the Kelvin cell.

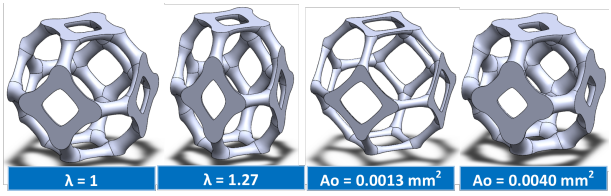

Figure 1: Some cell variants of the novel model

The benefit of a parametric approach is dual: if transferable to W foams, this model could be either tuned on available measurements or used for design optimization. Rather than imposing a limit to the maximum thickness of a porous armor owing to its high porosity, one could design the foam in order to fulfill functional requirements. For instance, it can be preliminary assumed that the thicker the armor, the greater the allowable number of transient events.

3. Scaling law development

Glancing at the global Fourier equation, thermal diffusivity α looks the key property during fast transients. Nonetheless, since thermo-physical properties of solid W (pedix s) are available in literature [12], the thermal diffusivity of a porous material can be expressed as a function of its relative density $\bar{\rho}$ and thermal conductivity k:

$$\alpha = \frac{k}{\bar{\rho}\rho_s c_{p,s}} \tag{3}$$

where $c_{p,s}$ and ρ_s are the specific heat and density of the solid material. Consequently, it was decided to deal with steady state characterization, where thermal conductivity k is relevant. At first, the transferability of the above described 3D model was investigated through model calibration with respect to the benchmark study [7] mentioned in section 1. Initially, k was assumed dependent on $\bar{\rho}$ through a material index C, as suggested in [8]:

$$\frac{k}{k_s} = \bar{\rho}^C \tag{4}$$

with k_s referred to the solid material. In order to allow the comparison, a foam having 100 ppi and approximately 8% of relative density was designed through model scaling. The cross section profile and cell anisotropy were kept as in [10]. In accordance with [9], a 0.8 mm thick foam layer was bonded to a 3 mm thick heat sink made of F82H RAFM steel. The resulting volume was then meshed with a total of 12763 *solid* elements and approximately 25000 nodes. Material properties valid in a broad temperature range were available in literature [12] (T in K for F82H, °C for W)

$$k_{F82H} = T(0.21 - 4.96\text{e-}4\ T + 4.98\text{e-}7\ T^2 - 1.84\text{e-}10\ T^3)$$
$$k_W = 174.93 - 0.11\ T + 5.01\text{e-}5\ T^2 - 7.83\text{e-}9\ T^3$$

No symmetry or heat losses were applied to the side faces. As described in [7], the coolant channel is placed at the bottom face of the heat sink, where helium flows at 400 °C, 10 MPa and 50 m/s. This results in a heat transfer coefficient of 10000 W/m^{2}K. Instead, the heat load was applied to the top surface of the foam. It was defined in order to allow the similarity in terms of heat flux exhausted by the heat sink. The resulting temperature distribution, in Figure 2, is in tight agreement with the benchmark study (relative difference between maximum temperatures around 0.25%), confirming the transferability of the model to W foams. In addition, k was evaluated equal to 5.62 W/mK, actually finding good agreement with measurements carried out by the firm Ultramet on similar W foams.

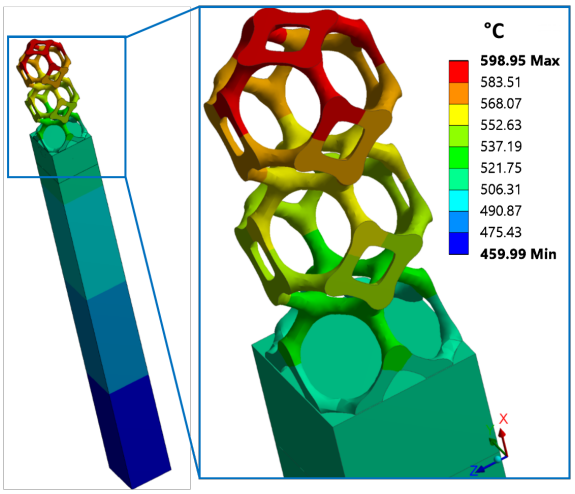

Figure 2: Temperature distribution after model calibration

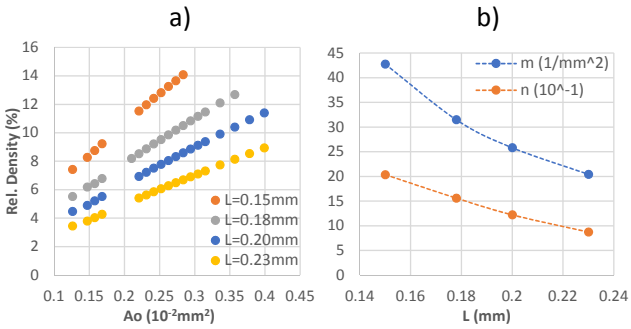

Figure 3: Regression analysis on relative density

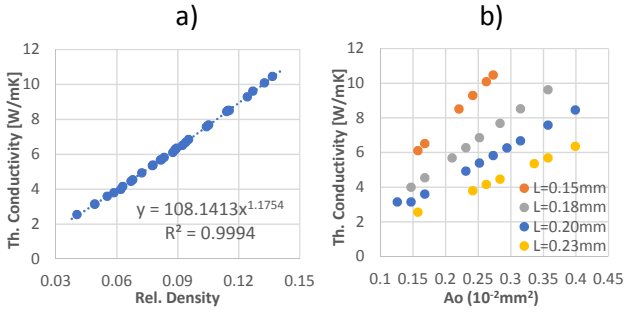

Figure 4: Dependence of k on $\bar{\rho}$ (a), L and A_0 (b)

As a further step, it was decided to extrapolate a parametric law for the thermal characteristics of foams having different geometrical features. Several combinations of ligament length L and reference cross section A_0 were obtained by varying the first within 0.15 – 0.23 mm, the second between $1.3 \cdot 10^{-3}$ and $4 \cdot 10^{-3}$ mm^2. For each value of L, a regression analysis was carried out, result-

ing in linear trends for relative density with respect to A_0, shown in Figure 3a. The influence of L was then taken into account through polynomials, respectively fitting the slope $m(L)$ and intercept $n(L)$ coefficients reported in Figure 3b and hereafter

$$m(L) = -1.78\text{e}4\ L^3 + 1.23\text{e}4\ L^2 - 3.00\text{e}3\ L + 2.76\text{e}2$$
$$n(L) = \ 5.16\text{e}2\ L^3 - 2.41\text{e}2\ L^2 + 20.47\ L + 2.65$$

Consequently, we could reshape $\bar{\rho}$ in order to include the impact of the chosen foam parameters:

$$\bar{\rho}(A_0, L) = 100 \cdot A_0 \cdot m(L) + n(L) \tag{5}$$

As observed, a significant increase in density seems to be possible with increasing A_0, and apparently this is even more pronounced at low L. Concerning the material index C, a detailed expression was achieved starting from the trend line in Figure 4a that correlates k to $\bar{\rho}$. By comparing this function with eq. (4), after few algebraic steps the following expression of the index C was obtained

$$C(A_0, L) = \ 1.1754 - \frac{\ln[k_s/108.1413]}{\ln[\bar{\rho}(A_0, L)]} \tag{6}$$

Ultimately, by replacing eq. (5) and (6) in eq. (4), a scaling law of the thermal response of W-based open cell foams can be achieved as a function of influential foam parameters:

$$k\ [W/mK] = k_s \cdot \bar{\rho}(A_0, L)^{C(A_0,L)} \tag{7}$$

The proposed scaling law offers the advantage of being theoretically applicable to a broad range of porous materials. It represents a reliable tool to face DEMO-like transient scenarios, tailoring the desired armor behavior from its constitutive features. In Figure 4b are shown the values of k obtained from the above described FEM analysis. They look spread between 2 and 12 W/mK, with the highest ones resulting from the combination of high A_0 and low L, as previously observed for $\bar{\rho}$. Thus, the initial hypothesis of linking k to $\bar{\rho}$ seems to be confirmed. In addition, this suggests that a future PFC, provided with a few mm thick foam armor, could rely on a weakly conductive and temperature resistant layer having acceptable steady state performances but experiencing material degradation during transients in order to prevent more severe failures. On the other hand, although allowing larger thicknesses, thick and short ligaments may lead to unacceptable mechanical behavior owing to hindered plastic deformation. Combined thermo-mechanical investigations and material characterization are therefore suggested.

4. Conclusion

In this paper, the promising application of W foams as sacrificial wall protection strategy for future reactors is investigated. As a first achievement, the scaling law of the thermal characteristics of W-based open cell foams was developed starting from a solid model originally validated for Al foams. The transferability to W was confirmed through a model calibration. The scaling law was then reshaped to involve the effect of the most influential foam parameters, allowing design optimization for functional requirements.

The main outlook of this activity is to deal with thermo-mechanical FEM analysis of foams under DEMO-like VDE TQ loads. Preliminary studies on this regard already provided encouraging results, when compared to those of the monoblock design. However, material characterization and further validation are needed. About this, the established manufacturing technologies of W may represent a further limitation.

Acknowledgment

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References

[1] F. Romanelli, et al, *"Fusion Electricity, A Roadmap to the Realisation of Fusion Energy"*, European Fusion Development Agreement, EFDA, Nov., 2012, pp. (2012).

[2] D.Stork et al., *"Developing structural, high-heat flux and plasma facing materials for a new-term DEMO fusion power plant: the EU assessment"* Nuclear Materials 455,277-291 (2014).

[3] F. Maviglia, et al., *"Wall protection strategies for DEMO plasma transients"*, Fusion Engineering and Design, 10.1016/j.fusengdes.2018.02.064 (2017).

[4] R. Wenninger, et al., *"The DEMO wall load challenge"*, Nuclear Fusion 57, 046002(11pp) (2017).

[5] F. Arbeiter, et al., *"Options for a high heat flux enabled helium cooled first wall for DEMO"*, Fusion Engineering and Design 119, 22-28 (2017).

[6] S. Pestchanyi, et al., *"Simulation of divertor targets shielding during transients in ITER"*, Fusion Engineering and Design 109-111, 141-145 (2016).

[7] S. Sharafat, et al., *"Micro-engineered first wall tungsten armor for high average power laser fusion energy systems"*, Nuclear Materials 347, 217-243 109-111 (2005).

[8] M. F. Ashby, et al., *"Metal Foams: A Design Guide"*, Butterworth Heinemann Ed. (2000).

[9] M. Andersen, et al., *"Thermo-mechanical analysis of a micro-engineered tungsten-foam armored IFE FW"*, Fusion Engineering and Design 81, 1639-1645 (2006).

[10] P. Fanelli, et al., *"Modelling and characterization of structural behaviour of Al open-cell foams"*, Materials and Design 114, 167-175 (2017).

[11] W.-Y. Jang, et al., *"On the crushing of aluminum open-cell foams: Part I. Experiments"*, International Journal of Solids and Structures 46, 617-634 (2009).

[12] ITER Organization, *"Historical Baseline Document: Appendix A, Materials Design Limit Data"*, Approved Version (2013).