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Tungsten filament mock-ups for gas box liner

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Abstract

Carbon impurities create carbon films saturated by tritium and deuterium onto the gas box liner. The reference gas box liner formed by chevron-shaped tungsten tiles is capable of depositing and/or recombining only 5% of the carbon impurities. The innovative solution presented here increases within the range 10^2 to 10^3 the surface interacting with the pumped gas by using an array of filaments, either disordered (felt) or ordered (spiral). This paper describes the experiments carried out to prepare felt/spiral samples and indicates possible ways of fabricating a representative gas box liner (GBL) mock-up. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Carbon impurities, under the form of carbon atoms, ions and hydrocarbon radicals, are produced in ITER during normal and off-normal operation as a consequence of physical and chemical sputtering and sublimation of the carbon-based armour of the lower vertical target. Eventually, the impurities are transported to the gas box liner (GBL), where they might form carbon films saturated by tritium and deuterium on the cold surfaces ($T < 500°C$) of the pumping duct and of the liner itself. The carbon films are likely to form in a recessed position, where they cannot be easily removed. The large tritium inventory thus created is unacceptable for a safe and economical operation of the reactor.

Experimentally, this phenomenon has been observed in the Mark IIa divertor of JET, where carbon flakes saturated with deuterium were predominantly found on the cold louvers behind the pumping slot [1]. This zone is characterised by a strong flow of gas through a region of high impurity fluxes, a similar situation to the working conditions expected in the ITER divertor.

Tritium co-deposition is strongly temperature dependent and can be largely reduced if carbon deposition occurs at high temperature. This is the approach of the reference GBL design, where the tungsten armour is shaped in such a way to protect the supporting structure from the surface heat flux and to condense the carbon impurities by letting them interacting with the hot tungsten surface at a temperature corresponding to a low tritium co-deposition rate ($T > 500°C$). The upper temperature limit is $\sim$1200°C to avoid tungsten recrystallization and the formation of brittle tungsten carbides. By adapting the cooling rate and the armour thickness to the local heat flux, which varies in the different liner locations from 0.1 to 0.8 MW/m^2, it should be possible to get the right armour temperature. According to recent estimates [2], the reference GBL operates in the right temperature range; however, the tungsten tiles area interacting with the exhaust gases is limited and can deposit a mere 5% of the carbon impurities. An increase by at least a factor 20 of the armour surface in the favourable temperature range is needed in order to allow the hydrocarbon radicals to undergo enough collisions for deposition.

This paper analyses possible ways to increase the surface interacting with the pumped gas by using, instead of solid tungsten tiles, an array of filaments, either disordered (felt) or ordered (spiral) in order to increase the surface interact with the carbon species by orders of magnitude with respect to the geometrical cross-section of the liner. The experiments carried out to prepare felt/spiral samples with varying armour thickness and filaments volume fraction and diameter are described, and possible ways of fabricating a representative GBL mock-up are schematically indicated.

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2. Analysis of the reference design and of alternative solutions

The reference GBL design along with some alternative solutions is schematically sketched in Fig. 1. The performance of the different geometries are evaluated by the surface multiplication factor (SMF) defined as the ratio between the effective area exposed to the exhaust gases and the geometrical cross-section of the component. Depending on the local heat flux, neutron heat deposition and cooling pattern, we can conservatively estimate that only a half of the exposed surface would be in the $500 > T > 1200$°C temperature range. Therefore, a SMF above ~ 40 is actually needed.

Other factors to be taken into account in the choice of the GBL design are the vacuum conductance, the ease of fabrication, the resistance to normal and off-normal heat loads, the effect of neutron irradiation on the armour material.

2.1. Reference armour [3]

The liner is clad with chevron-shaped tungsten armour blocks on stalks set in a cast pure Cu matrix, which is subsequently EB welded to a CuCrZr heat sink, which incorporates the coolant channel (Fig. 1(a)). Apart from its poloidal geometry, this plasma facing component differs from the vertical target in that 8 mm poloidal slots or openings are incorporated in the upper section of the liner, through which gas from the divertor channel is exhausted into the pumping ducts in the cassette body. Chevron-shaped W armour blocks on stalks replace the macro-brush of the vertical target. The chevron blocks have approximate dimensions of $50 \times 35 \times 6$ mm^3 thick, and the reduced cross-section stalks to provide a reduced thermal conductance. In this way, the stalks allow the plasma facing surface of the liner to be operated at between 500°C and 1200°C over the most likely heat flux range 0.3–0.8 MW/m^2, while minimizing trapping of tritium through co-deposition with carbon. The chevron avoids line of sight through the liner to the cold surfaces of the support structure. The SMF of the chevron tiles is ~ 5, largely insufficient to deposit the totality of carbon impurities. However, the design is suitable thermal-hydraulically and mechanically for heat flux up to and beyond 1 MW/m^2.

2.2. Radiative W-tiles

An alternative design consisting in tungsten tiles of a simple geometric form (Fig. 1(b)) has been proposed by Archipov et al. [2]. The tiles are loosely fastened to the cooled structure to minimize conductive cooling in favour of radiative cooling with the following advantages: more uniform tile temperature and greater hot area; the tile does not have to be rigidly fixed to the support structure, thereby separating the high temperature tile from the cooled structure; if the tile overheats due to disruption loads then there is no braze joint to damage or Cu interlayer that may creep; the re-radiated load to the heat sink can be low enough to eliminate the copper heat sink leaving only the steel support structure thus simplifying the design and minimizing the cost. However, the SMF of this geometry is ~ 3, largely insufficient for the complete deposition of carbon impurities.

2.3. Felt geometry

Tungsten felt is easily commercially available at low cost, since it is a by-product of the electric-light bulb fabrication. Tungsten fibres are first cleaned with caustic soda, then, rinsed in water and, then in ethanol with ultrasonic and dried. The felt is formed by compressing the fibres of diameter d to the required volume fraction V_f and thickness t. The required tile shape is stabilized by a thermal treatment. The felt tile is brazed to the copper heat sink as in the reference ITER design. A schematic drawing of the proposed solution is shown in Fig. 1(c). Fig. 2 shows the SEM microstructure of a felt with tungsten wire diameter $d = 25$ μm, a volume fraction $V_f = 15\%$ and an armour thickness $t = 13$ mm. By simple geometrical considerations, it turns out that

$$\mathrm{SMF} = 4tV_f/d. \tag{1}$$

The SMF of the tungsten felt shown in Fig. 2 is ~ 310.

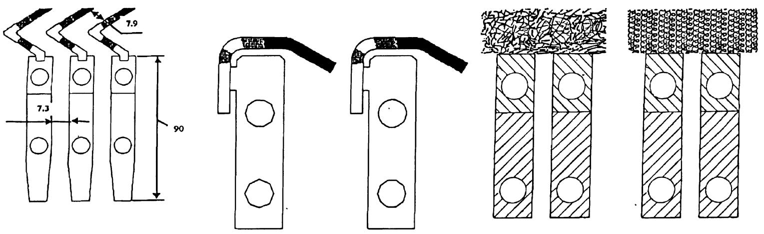

Fig. 1. Design geometry of the liner elements: (a) reference design; (b) radiative tiles; (c) felt tile; (d) double spiral tile. SMF is the ratio between the effective area exposed to the exhaust gases and the geometrical cross-section of the component.

Fig. 2. SEM microstructure of a felt tile. The felt parameters are: $d = 25$ μm, $V_f = 15\%$ and $t = 13$ mm.

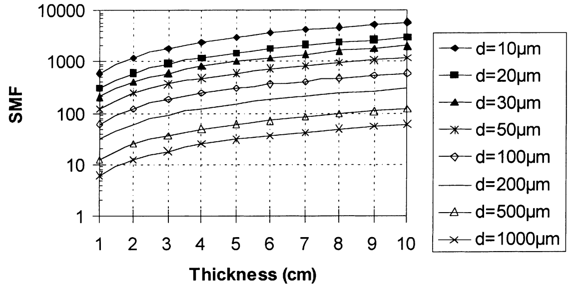

Fig. 3. SMF of the felt liner as a function of the tile thickness for different fibre diameters (in micrometers) and $V_f = 15\%$.

Fig. 3 reports the SMF of a felt armour as a function of the armour thickness, for $V_f = 15\%$ and d ranging from 0.01 to 1 mm. The liner surface can be increased by orders of magnitude ($10 < \mathrm{SMF} < 100\,000$) by varying the parameters t, V_f , and d in the range: $10^{-2} < t < 10^{-1}$ m, $10 < V_f < 30\%$, $10^{-6} < d < 10^{-3}$ m.

2.4. Double spiral geometry

Tungsten double spirals are commonly used in many lighting applications. The first spiral is wound round a molybdenum core and then the second spiral is formed around a molybdenum core of larger diameter, as shown in Fig. 4. The diameter of the large spiral is 0.386 mm, the wire diameter $d = 20.34$ μm. At the end of the forming process, the molybdenum core is removed by chemical etching. The production technology of the double spirals is well established and a large variety of tungsten wire diameters and spiral dimensions can be produced at relatively low cost. The armour is assembled by interweaving the spirals each other and inserting a small portion of the spirals into copper by the well-developed active metal casting process. The armour is finally brazed or welded to the water-cooled heat sink. Fig. 1(d) shows a schematic drawing of the double spiral armour. Fig. 5 shows a set of spirals placed side by side and not interwoven before the chemical etching to dissolve the molybdenum core.

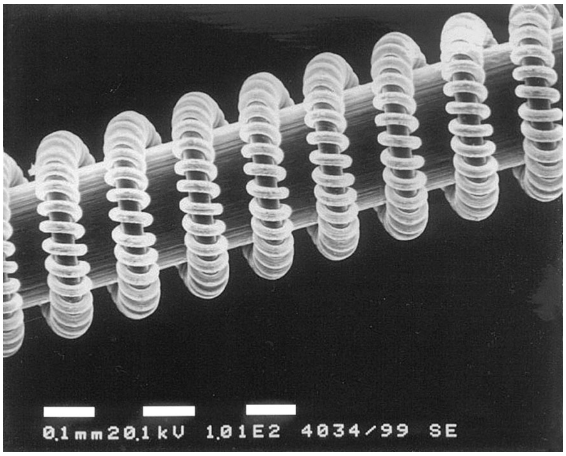

Fig. 4. Fabrication process of the double tungsten spiral. The SEM picture shows the fine spiral wound around the molybdenum core.

The SMF of the double spiral geometry cannot be derived by the expression (1), because V_f is not a simple function of the spiral geometry and layout, but by weighing a single double spiral. In an armour where the spirals are placed side by side and not interwoven with $d = 0.02$ mm, $t = 30.6$ mm, the weight is 7×10^{-3} g, $V_f = 10\%$ and SMF $\sim$ 500.

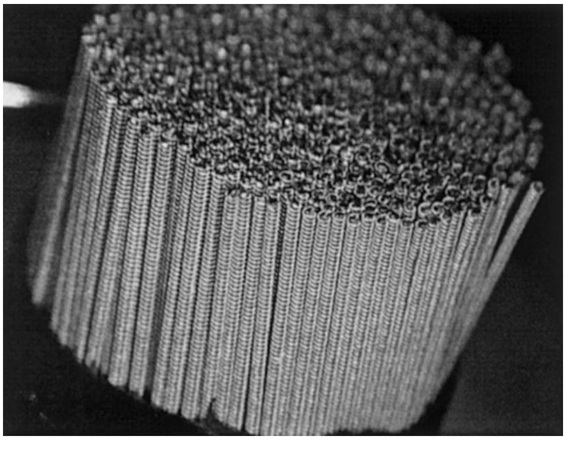

Fig. 5. Set of spirals placed side by side and not interwoven before the chemical etching to dissolve the molybdneum core.

2.5. Comparison between the two armours.

Attempts are at present carried out to prepare felt and spiral armour samples and thereafter a representative GBL mock-up to optimize the armour design and to validate its carbon filtering efficiency as a function of the number of normal cycles and plasma disruptions.

The analyses and limited number of tests carried out so far, indicate that both geometries can easily reach a $\mathrm{SMF} > 40$. The optimization of the geometry and the choice of the most suited armour for the GBL can only be made after a deeper characterisation of both armours, including the measure of the through thickness thermal conductivity, carbon deposition rate, hydrogen inventory in the co-deposited film, fibre loss due to carbide formation and/or recrystallization, behaviour under plasma disruption (Q up to 10 $\mathrm{MJ/m^2}$), vacuum conductance, thermal fatigue behaviour under normal conditions for the design number of cycles and reactivity with steam as a function of temperature.

From the technological point of view, the felt is easier to be fabricated with a similar cost, if not cheaper, than the cost of the reference design.

The regular pattern of the spiral armour holds promise of a much higher vacuum conductance and better surface related properties, since it achieves a larger SMF, V_f being equal.

Both felt and spiral tiles are certainly more resistant than the chevron tiles under thermal fatigue because of the loose character of the tile. The latter advantage is even more important, when considering the embrittlement, which occurs in tungsten already at the level of 0.01 dpa.

The choice of the fibre diameter is dictated by the effect of plasma disruptions. During plasma disruptions, the re-radiation due to the vapour shielding effect on the vertical target causes an energy deposition of up to 10 $\mathrm{MJ/m^2}$ onto the GBL. The tungsten erosion is determined by the loss of melted layer and under this energy density is estimated to be up to 100 μm. In order to extend the GBL lifetime, it is advisable to use fibres with such a diameter.

3. Summary and conclusions

The presence of carbon films saturated by tritium and deuterium onto the cool parts of the GBL is unacceptable for a safe and economical ITER operation. The reference GBL is designed with chevron-shaped tungsten tiles, which is capable of depositing and/or recombining a mere 5% of the carbon impurities. The concept presented here aims at increasing the surface interacting with the pumped gas. The solid tungsten tiles of the reference design are replaced by an array of filaments, either disordered (felt) or ordered (spiral). The performance of two options is evaluated by the SMF, defined as the ratio between the effective area interacting with the exhaust gases to the cross-section of the component.

Both felt and spiral armours appear to be very efficient since the SMF can be orders of magnitude higher than that of the reference GB and thus should allow a complete removal of carbon impurities without tritium co-deposition.

References

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[3] ITER Final Design Report, DDD 1.7, Paragraph 2.1.2.