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Options for a high heat flux enabled helium cooled first wall for DEMO

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HIGHLIGHTS

- Design challenges for helium cooled first wall reviewed and otimization approaches explored.
- Application of enhanced heat transfer surfaces to the First Wall cooling channels.
- Demonstrated a design point for 1 MW/m^2 with temperatures <550 °C and acceptable stresses.
- Feasibility of several manufacturing processes for ribbed surfaces is shown.

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ABSTRACT

Helium is considered as coolant in the plasma facing first wall of several blanket concepts for DEMO fusion reactors, due to the favorable properties of flexible temperature range, chemical inertness, no activation, comparatively low effort to remove tritium from the gas and no chemical corrosion. Existing blanket designs have shown the ability to use helium cooled first walls with heat flux densities of 0.5 MW/m^2. Average steady state heat loads coming from the plasma for current EU DEMO concepts are expected in the range of 0.3 MW/m^2. The definition of peak values is still ongoing and depends on the chosen first wall shape, magnetic configuration and assumptions on the fraction of radiated power and power fall off lengths in the scrape off layer of the plasma. Peak steady state values could reach and excess 1 MW/m^2. Higher short-term transient loads are expected.

Design optimization approaches including heat transfer enhancement, local heat transfer tuning and shape optimization of the channel cross section are discussed. Design points to enable a helium cooled first wall capable to sustain heat flux densities of 1 MW/m^2 at an average shell temperature lower than 500 °C are developed based on experimentally validated heat transfer coefficients of structured channel surfaces. The required pumping power is in the range of 3–5% of the collected thermal power. The FEM stress analyses show code-acceptable stress intensities. Several manufacturing methods enabling the application of the suggested heat transfer enhanced first wall channels are explored. An alternative cooling technology is suggested, extending the tolerable heat loads up to 3 MW/m^2.

1. Introduction

The use of high pressure helium gas as coolant medium for the First Wall (FW) is foreseen for several blanket concepts (Helium Cooled Pebble Bed (HCPB), Helium Cooled Lithium Lead (HCLL), Dual Coolant Lithium Lead (DCLL)) for the EU DEMO [1] and has already been developed to sustain moderate heat flux densities in the range of 250–500 kW/m^2, supported by analyses [2–4] and experiments [4]. The main advantages of helium as coolant are: (1) the flexibility to match the structural material's upper and lower temperature limits, (2) safety aspects such as chemical inertness (avoid reactions with neutron multiplier or breeder materials), no activation, comparatively low effort to remove tritium from the gas, and (3) no chemical corrosion. Among the challenges for helium as coolant medium are the lower product of density and heat capacity and lower thermal conductivity. This leads (1) to larger required pumping power for the same cooling as well as (2) to usually wider cooling channel cross sections, which give rise to bending stresses

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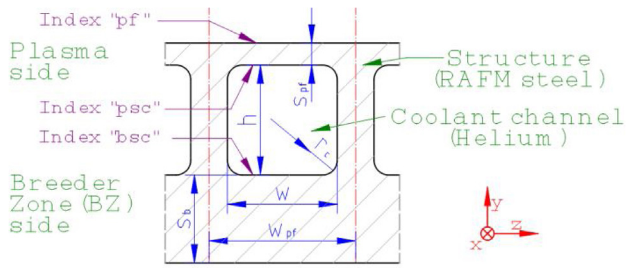

Fig. 1. Naming convention for orientation and measures of a FW channel element (cross section shown).

in the plasma sided channel cover. This paper proposes measures to deal with the above-mentioned challenges.

2. FW thermal-mechanical loads

Several studies were published recently on the expected FW thermal loads in the EU DEMO. Radiated power was estimated up to 450 kW/m^2 [5], and additional peak loads by thermal charged particles were estimated up to 650 kW/m^2 [6] or even in the several MW/m^2 region for cases where the FW surfaces intersect with the magnetic field lines (which is the case for some suggested FW contours) [7]. Peaking of the heat flux density vs. the average value makes the FW/blanket cooling design complicated and the balance-of-plant less efficient, because the ratio of harvested thermal power vs. the pumping power ($\dot{Q}_{th}/P_{pump}$) drops progressively for higher heat flux densities [8]. The additional presence of large uncertainties of the heat flux density for a certain module/location requires dimensioning for the highest anticipated value (to exclude component failure), which results in over-cooling (too low outlet temperature, too high pumping power) when this highest anticipated value is not reached in operation. This is true for all cooling media, and calls for designing the plasma and the FW to reach a balanced surface power load distribution with a high quality of prediction. For a machine like DEMO, residual uncertainties have to be accepted in the design phase, and the priority of machine safety exceeds the objective of net electricity output.

In the view of the above cited anticipated heat flux densities, R&D for helium cooled first wall designs is ongoing: One set of concepts strives to provide solutions for up to about 1 MW/m^2 for the large parts of the FW surface. These solutions aim to be compatible with integrated as well as detached [9] FW concepts. Other concepts aim at very high heat fluxes (Objective: up to 5 MW/m^2) predicted for the hot spots, applicable mainly for detached FW concepts or limiters.

Apart from the thermal loads the FW channel walls are also loaded by the static pressure of the coolant. The internal pressure of the helium coolant is uniformly set to 8 MPa in all helium cooled concepts.

3. Optimization approaches

The optimization approach in this study is not specific to a certain blanket/FW design and thus does not adopt specific mechanical constraints from such designs. Quadratic (w = h) channels as shown in Fig. 1 are considered. The included loads are the thermal loads from the plasma (and with less magnitude from the breeder zone (BZ) side), which induce secondary stresses by temperature gradients, and the internal pressure loads from the cooling channels which induce primary membrane stresses as well as primary bending stresses.

According to [10] for an edge-held flat rectangular plate with thickness s_{pf} due to internal pressure load p the maximum bending stress is according to Eq. (1)

$$\sigma_{pb} = p \cdot \frac{\beta \cdot w^2}{s_{pf}^2} \quad \text{with } \beta = 0.5 \tag{1}$$

and the stress due to a temperature difference in a body is approximated by Eq. (2)

$$\sigma_{DT} = \Delta T \cdot \gamma \cdot E \cdot (1 - \nu) \tag{2}$$

where γ is the coefficient of linear thermal expansion, E is the Young Modulus, and ν (0.3 for steel) the Poisson ratio. The true magnitude of the temperature-induced stresses depends strongly on the applied mechanical constraints. For cases with thin dividing walls the temperature difference within a channel cross section can be estimated by

$$\Delta T = \dot{q}_{pf} \left(\frac{1}{h_{psc}} + \frac{s_{pf}}{\lambda_w} \right) \tag{3}$$

where $\dot{q}_{pf}$ is the incident heat flux density from the plasma, h_{psc} is the heat transfer coefficient on the plasma sided channel surface, and λ_w is the wall thermal conductivity. Thermal stresses are however not only caused by the heat flux through the plasma sided channel cover, but also by temperature differences over the complete component (see also Section 3.2).

Both stress components act in the same sense on the plasma side channel cover shell surfaces near the dividing walls where they add up to a maximum. The indicative Eqs. (1)–(3) explain that stress-optimization for a high heat flux FW implies a trade-off for the channel cover thickness s_{pf}. The optimum value of s_{pf} is a function of material properties and especially the requested wall heat flux density $\dot{q}_{pf}$: the higher $\dot{q}_{pf}$, the lower s_{pf} must be chosen.

The stress assessment for normal operation includes the criteria of Eqs. (4) and (5) [11] which are highlighted here because they were found to be the limiting ones in the designs studied for this paper.

$$\overline{P_L + P_b} \leq 1.5 \cdot S_m \left(\theta_m \right) \tag{4}$$

$$Max \left(\overline{P_L + P_b} \right) + \Delta Q \leq 3 \cdot S_m \left(\theta_m \right) \tag{5}$$

$\overline{P_L + P_b}$ is the primary membrane- plus bending stress intensity, ΔQ the secondary stress range and $S_m \left(\theta_m \right)$ the material's allowable stress for the temperature θ_m averaged over the thickness of the shell. In order to conservatively limit creep issues, the condition $\theta_m < 500\,^\circ$C was also satisfied.

The followed optimization approach addresses the following elements:

- Heat-transfer-enhancement: Increasing material strength (yield $S_y \left(\theta_m \right)$ or creep rupture $S_r \left(\theta_m \right)$) by *globally decreasing* the material temperature.
- Heat-transfer-tuning: Locally adapt the heat transfer coefficients to *equalize* the component temperature field.
- Optimizing the shape of the load-carrying structural material around the channel to reduce stresses.

3.1. Heat transfer enhancement

In the follow-up of promising scoping studies [8,12], a number of heat transfer enhancing structure configurations has been investigated using scale resolving CFD methods [13,14]. The delayed Detached Eddy Simulation (DDES) approach for the transverse sharp-edged ribs (TER) was validated by dedicated experiments