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Thermomechanical analysis of a Flow Channel Insert based on a SiC-sandwich material concept

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ABSTRACT

The Dual Coolant Led Lithium (DCLL) blanket is one of the concepts being investigated as candidate for DEMO, due to the high thermal efficiency provided by the flowing PbLi self-cooled breeder at ≈700 °C in the high temperature design. Key elements are the Flow Channel Inserts (FCIs) serving as electrical and thermal insulators to mitigate MHD effects and to keep the He-cooled steel walls below its maximum allowable temperature due to corrosion. A material based on sandwiching porous SiC between dense SiC layers is proposed for FCIs. In this work results of theoretical calculations and an FEM model are presented to determine the optimum thickness of both porous core and outer dense layers to assure the required thermal insulation across the FCI with minimum thermal stresses, considering achievable properties for the porous SiC material and its fabrication possibilities. It is concluded that the porous core thickness must be at least 5 mm if a porous SiC with thermal conductivity around 7 W/mK is used; a dense coating of ≈200 µm is considered as optimum regarding the thermal stresses present in the FCI.

1. Introduction

One of the four European blanket concepts that are being considered for its application in a future DEMO reactor is the Dual Coolant Lead Lithium (DCLL) one [1]. In the high temperature DCLL design, a eutectic Pb-15.7Li alloy flows at a relatively high velocity (≈10 cm/s) through long poloidal channels, acting as self-cooled breeder and absorbing the neutron flux energy in order to achieve the highest possible power conversion. Candidate structural materials in the DCLL blanket are focused on reduced activation ferritic/martensitic steels, with a maximum allowable creep temperature of ≈550 °C and a maximum allowable PbLi interface temperature of ≈470 °C due to corrosion [2–3]; helium is used to cool this blanket steel structure as well as the first wall. In the high-temperature DCLL blanket concept for DEMO, liquid PbLi could reach temperatures around 700 °C, providing net efficiencies around 45%, i.e. considerably higher than those achieved in other blanket designs [4].

In order to minimize heat losses from the volumetrically heated liquid breeder to the helium-cooled steel walls and to decouple electrically the flowing liquid metal (LM) from the electrically conducting wall, key insulating structures called Flow Channel Inserts (FCIs) are needed. FCIs are supposed to be hollow poloidal ducts with a thickness of a few mm, being loosely fitted into the LM channels and containing the hot PbLi inside them. There is a thin PbLi filled gap between the inserts and the steel structure, allowing for different thermal expansion and irradiation induced swelling [5].

Silicon carbide (SiC) is a suitable candidate material for FCIs. However, the need for low electrical and thermal conductivity of the FCI structure, in addition to its necessary integrity and reliability against corrosion, require substantial R&D efforts in material development and fabrication techniques of new SiC based materials. Firstly, different SiC/SiC composites have been proposed as FCI structural materials [6-8]; however, internal stresses due to differential irradiation swelling can be a major integrity issue for this kind of materials [9], apart from the difficulty of obtaining and processing them. Alternatively, a material based on sandwiching porous SiC between dense SiC sheets produced by Chemical Vapour Deposition (CVD) has been proposed, with low cost and ease of fabrication compared to SiC composites [3]. Specifically, thermal conductivity has to be appropriately reduced to allow the necessary thermal insulation between the steel structure and the hot PbLi inside the channel; this would result in a high thermal gradient across a few mm thick closed channel, producing thermally derived mechanical stresses that the highly porous SiC material should withstand. Thus, some additional stresses

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resulting from the presence of two different materials across the FCI's sandwich structure will be present, so that the porous-SiC material must have enough mechanical integrity to withstand these thermal stresses. In order to assure FCIs structural reliability it is necessary to determine the value of these stresses.

The aim of the present work is to determine the value of the thermal stresses that will be present in a SiC-sandwich structured FCI, as well as the necessary thermal conductivity and material thickness to assure the required thermal insulation. With that aim, a thermomechanical analysis of FCIs is presented, using analytical calculations and FEM simulations. In parallel to the present study, a new method for producing a porous SiC material with the necessary low conductivities and mechanical integrity is being developed, so that the analysis results will be compared to the achievable properties of a possible porous SiC material, in order to project accurate designs. Finally, two possible configurations of FCIs are proposed based on the results and the material production possibilities. Experimental results of the porous-SiC production method will be published in a future work.

2. Functions and requirements of the FCI material

Some key performance requirements have to be met by the FCI structure:

- *Thermal insulation:* As mentioned in the previous section, to provide enough thermal insulation is one of the main functions of the FCI structure, especially in the "through-thickness" direction. This requirement arises from the fact that the PbLi-steel interface cannot reach temperatures above ≈470 °C due to corrosion damage, while the PbLi temperature should be up to ≈700 °C in order to ensure highest possible net efficiencies; the thermal decoupling of the steel wall and the hot PbLi is required to assure blanket integrity and its efficiency. The complete insulation that the FCI provides across its walls depends basically on its thermal conductivity and on the wall thickness; in the following sections, optimum values for these parameters will be discussed.
- *Mechanical integrity:* Although the FCI does not have a structural purpose, thermally derived stresses will be present as mentioned above. FCI's material must exhibit enough mechanical strength to withstand them as well as some possible additional stresses, as can be the ones derived from the different radiation induced swelling of dense and porous SiC [10], or by temperature differences within the channel due to volumetric heating [11]. A study of the primary thermal stresses resulting from the thermal gradient across the insulating walls will be presented in the sections below.
- *Electrical insulation:* It is necessary to electrically decouple the hot flowing PbLi and the steel structure in order to minimize the magnetohydrodynamic (MHD) effects that would be present in PbLi during blanket operation. They arise from the fact that a conductive fluid is moving with a considerably high velocity under the influence of the strong toroidal magnetic field, originating Lorentz forces which disturb the flow profile. Some of the MHD phenomena that may arise during the operation are PbLi pressure drop, the formation of high-velocity near-wall jets or a modification of the flow properties through turbulence transitions and mixed convection effects [12-13]. A study of the electrical conductivity of the FCI material will not be addressed in this work, but to determine the optimum value to reduce these phenomena is essential for a correct FCI performance. An electrical conductivity of <20 S/m seems to be enough to provide a good insulation [14]. However, lower electrical conductivities could generate considerable temperature differences between the walls of FCIs which are parallel to the magnetic field and the perpendicular ones; this situation will result in additional thermal stresses, according to [11]. Further studies including the possible value of these stresses as well as more design optimizations are needed.
- *Reliable sealing of all FCI's surfaces, including hot PbLi corrosion effects:* The FCIs will be in contact with flowing hot PbLi over the whole operation time (3–5 years [5]). Thus, laboratory tests on SiC-sandwich materials have to be performed in order to assess the capability of the dense CVD-SiC layer to prevent failure by corrosion. Corrosion tests under static PbLi at temperatures of 700–800 °C and under flowing PbLi at 550 °C in presence of a 1.8 T magnetic field will be performed on the SiC sandwich material that is being produced at Ceit, whose results will be published in future works.

3. Problem formulation and results

3.1. Material concept

The FCI material concept proposed in this work is based on the SiC-sandwich model. The core is made of a porous SiC material which has to exhibit the required low electrical and thermal conductivity in order to fulfil the requirements discussed above, as well as sufficient mechanical strength. As mentioned before, a method to produce porous SiC with the desired porosity and strength is being developed at Ceit; in this method, thermal and electrical conductivity will be tailored by controlling porosity, aiming at obtaining an acceptable mechanical strength by disposing porosity following a honeycomb structure. Porosity will be introduced using the sacrificial template technique. Subsequently, a dense CVD-SiC layer will be deposited, with the required thickness to provide a reliable porous core sealing but without obstructing the insulation requirements, since CVD-SiC has relatively high thermal and electrical conductivities. Furthermore, the elastic modulus of CVD-SiC is an order of magnitude higher than the one of porous SiC. Thus, important mechanical stresses may be present in the dense sheet; the value of this maximum stresses depends on the thickness of the dense layer and on the thermal conductivity of the porous core. Therefore, these design parameters have to be fixed allowing the FCI to fulfil its required functions while maintaining the maximum flexural stresses on the dense layer below the allowable CVD-SiC limit.

3.2. Thermal analysis

3.2.1. Calculation model

The maximum temperature of the RAFM steel structure is close to 470 °C, while the liquid PbLi inside the channel is reaching a temperature near 700 °C. Thereby, it is necessary to ensure a minimum insulation of ≈230 °C across the FCI walls.

The insulating character of a FCI sandwich material depends mainly on the porous-SiC core characteristics: its thickness and thermal conductivity. To study the dependency of the FCI's walls insulation on these parameters, a 1D heat transfer problem has been considered, by modelling the heat flow along the radial direction of the channel. The dense CVD-SiC coating has not been taken into account since its thickness is much smaller and its thermal conductivity much higher than those of the porous SiC core, thus practically not contributing to the insulating properties of the FCI. A sketch of the problem statement is shown in Fig. 1, where heat flows from the hot PbLi through the FCI to the 300 °C helium [1,6] that is cooling the RAFM structure. It is assumed, as calculation hypothesis, that the temperature of the inner wall of the FCI (T1) remains equal to the LM average temperature, i.e. 700 °C (due to the lack of correlations for the heat transfer coefficient of PbLi under a high magnetic field, the worst scenario has been assumed).