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DEMO Breeding Blanket temperature evaluation before remote maintenance operation

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DEMO Breeding Blanket temperature evaluation before remote maintenance operation

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In DEMO the Breeding Blanket (BB) segments shall be periodically replaced, at end of life or after failure. Any replacement of a BB segment shall be performed by Remote Handling Equipment (RHE) through the vertical upper port: any active action is executed by RHE that clamps a BB segment in the upper portion using a BB transporter. A driving requirement of DEMO commercial technology for RHE is its maximum operating temperature at the BB-RHE interface during BB replacement: the objective of this study is properly to assess this limit, being now the allowable value at 100°C. This study deals with the Helium Cooled Pebble Bed (HCPB) concept.

The initial configuration is considered i.e. with all the BB segments sector (three outboard and two inboard segments) in place, and with some simplifications, the Finite Element model tries to predict if a cooling air flux in natural convection conditions inside vacuum vessel is adequate or if a cooling air flux with forced convection conditions must be adopted. The decay heat produced by the main blanket components (the BB modules caps and lateral walls, the backwalls, the supporting structures, the backplate manifolds, and so on) have been evaluated beforehand: the values applied as body loads in the thermal analyses have been selected within the set related to one month after shut-down. With the assumed geometrical and physical boundary conditions set for the natural and forced convection, the analyses indicate that a forced convection could be necessary to ensure compliance with the present RHE requirements. The obtained results, the analysis assumption and future analysis plan have been briefly discussed.

Keywords: DEMO, Breeding Blanket, FEM, thermal analysis

1. Introduction

This work is inserted in the frame of the tokamak design that is used to study the nuclear fusion matters. Some general descriptions of this scientific environment can be found in [1-3]. This study deals with the temperature inside the DEMO vacuum vessel before conducting any remote maintenance operation. As the components inside the vessel must be replaced after a predefined period, the first problem is the evaluation of components temperature when it will be substituted. The decay heat produced by the blanket breeding modules during the shutdown period is the most important physical quantity in determining the temperature inside the vessel. As the in-vessel components are actively cooled during the shutdown phase, the decay heat produced by the irradiated breeding blanket (BB) segments can be considered removed and exhausted by the cooling system until the cooling is turned off and the cooling pipes are disengaged. But whatever the period would be, when the RHE is called to operate inside the vessel, the need to avoid its materials breakdown dictates the operating temperature control. Currently, the Remote Maintenance (RM) temperature limit for the BB and RHE interface during replacement operations is assumed to be 100 °C: beyond this the RHE requirements are more demanding and the active cooling of the RHE is mandatory thus increasing complexity.

The maximum nuclear rated operating temperatures for some elements of standard technology are: motors 220 °C, resolver 125 °C, lubricants 260 °C, wiring 250 °C. It is certain that up to 60°C the standard components can operate safely; the range 60-120°C can be considered high temperature but the related components are still available off-the-shelf, above 120°C specific components are necessary.

This analysis evaluates the temperature during the RHE intervention and it establishes if the natural convection inside the vessel is enough to allow the introduction of the RM manipulator. Another attempt has regarded the temperature evaluation supposing forced convection with an air flow inside the vessel during the aforementioned RM operations. The region that identifies the BB-RHE interface is shown in fig.1 (traced surface) and it will be these supports whose temperature will be verified.

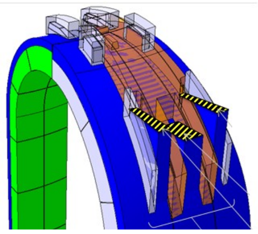

Fig. 1: traced surface for manipulator support with interfaces of BB-RHE marked

2. New blanket geometry

The DEMO blanket geometry was improved in the previous years as reported in [4]: its main function is to produce the tritium for the maintaining of the nuclear reaction. The old blanket geometry foresaw a segment subdivision [3] in some modules containing all the structural and functional materials needed to breed the reaction. Every module contained the breeding units formed by the cooling plates enveloping the breeder material (Li_4SiO_4) formed by a pebble bed; the remaining

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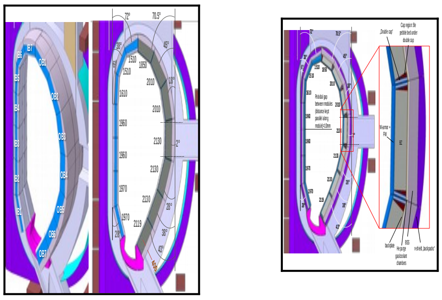
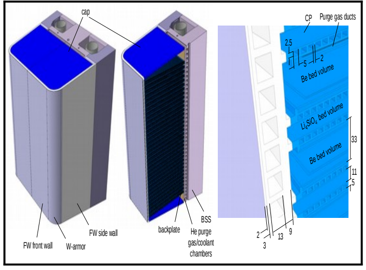
Breeding Unit (BU) volume was filled with beryllium neutron multiplier in form of a pebble bed. The previous geometry has been fully revised as reported in [4]: the basic nuclear, thermo-hydraulic and thermo-mechanical functions have been improved and the components manufacturing has been symplified.

In [4] there is a complete explanation of the new geometry: here the main improvements related to this new concept will be taken on, that is the questions related to the aforementioned temperature evaluation problem. The fig.2 reports a new geometry plot: in the left part there is an image of a whole blanket sector (2 inboard and 3 outboard segments) and at the right there is a detailed image of a single module.



(fig.2: blanket sector drawing with one module details)

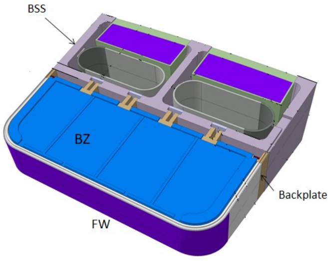
Also now the single blanket segment has been divided in some modules resulting in a castellated structure that allows to release the thermal stress. In the fig. 3 there is a detailed view of the single module.



(fig.3: HCPB blanket module with vertical cross section)

Every module is constituted by a First Wall (FW) (25 mm thick) made of Eurofer with a thin plasma facing tungsten layer (2 mm thick). The FW of all BB modules have been foreseen with a bending radius at the toroidal edges. The internal stiffening grid was simplified leaving only the horizontal cooling plates inside the module. These separate the Li_4SiO_4 bed volume (11 mm thick) from the Beryllium one (33 mm thick).

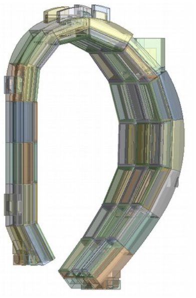
The single BB is formed by joining the FW, the caps and backplates enclosing a Breeding Zone (BZ) volume, which is fixed at the Back Supporting Structure (BSS). The overall geometric arrangement is shown in fig.4.



(fig.4: HCPB module cross section: BSS, FW, BZ, Backplate)

2. FEM model

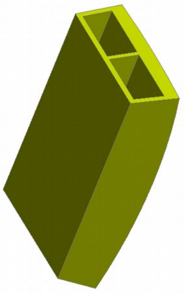
Fig. 5 shows the FEM model of the blanket segments in one sector generated from the CAD model [5].



(fig.5: blanket sector cad model)

The loads required to evaluate the temperature evolution during shutdown were determined with a neutron analysis that determined the radioactive isotopes generated in the BB that cause the decay heat [6]. These values have been defined and applied in the FE model individually for First Wall, Breeding Module, Back Supporting Structure and Manifold of each module at some relevant time instants (1 s, 1 h, 1 day, 1 week, 1 month, etc.) after plasma shutdown.

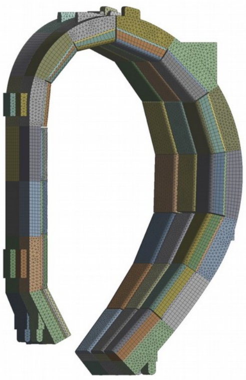
The BSS solid model has been sub-divided in separate poloidal volumes, see fig. 6.



(fig. 6: example of a BSS sub-volume)

This joint between the backwall of each breeding module and the corresponding volume of the back supporting structure has been simulated with contact and target elements (always bonded option).

Since most volumes are filled with a material mixture homogenized values were defined based on the material mix in the respective zone according to the BB design [6]. After all these preparatory steps, the final mesh (fig. 7) has been obtained. The employed software has been Ansys release 18.2 [7].



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(fig. 7: mesh for all BB modules and all BSS components)

3. Thermal analysis

The thermal boundary conditions considered in the analyses are summarized tab.1.

Parameters	Natural convection	Forced convection
Initial temperature on BB modules and on BSS volumes	300	300
Air bulk temperature inside the vessel (front side of FW) (°C)	300	25
Air bulk temperature inside the vessel (back side of BSS) (°C)	150	25
Convective film coefficient (W/(m^2 °C))	10	200
Ambient temperature for radiation simulation (°C)	150	25
Emissivity for radiation simulation (grey body)	0.8	0.8
Duration of the simulation (days)	1	1
Initial time of simulation (time after shutdown) (months)	1	1

(tab.1: assumptions and initial values for thermal analysis)

The BB modules initial temperature and the in vessel air bulk temperature have been 300 °C; the BB modules decay heat is supposed to be exhausted by the BB cooling system when the vessel is closed; the air bulk temperature inside the vessel at the back side of the BSS (150 °C) is a mean value between the situation in the central plasma region and the "limit layer" near the internal VV surface that is supposed to be actively cooled. The convective film coefficients and the irradiation parameters have been taken from ordinary technical literature for the same reason [8].

Natural convection has been envisaged and it allowed to evaluate if it is suitable to cool the vessel volume till to RHE requirements (100 °C on the interface for blanket transporter tool); then also the forced convection has been analysed to decide about the necessity to install the cooling plant. Every analysis has been thought to last for one day: this choice has been verified afterwards as it was clear that the temperature time history of any node placed in the aforementioned surface of transporter tool support has a value near to the "asymptotic" one.

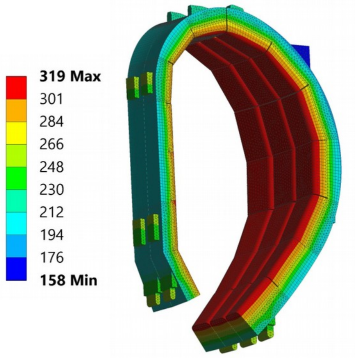
In fig. 8 are shown plasma-facing BB surfaces with defined convection conditions (left) and external BSS surfaces with defined radiative heat exchange (right).

(fig.8: BB and BSS surfaces loaded with convection (left) and radiation (right))

Surface convection has been defined on the BSS backside as they are in front of the vacuum vessel upper port and this type of heat exchange is supposed to happen. The decay heat powers assumed for the analysis are related to one month after shutdown.

Also the radiation between the backside of BSS and the VV inner shell has been considered: for both cases "Emissivity=0.8" (grey bodies) and "Ambient Temperature = 25° C" (forced convection) and "Ambient Temperature = 150° C" (natural convection) have been chosen.

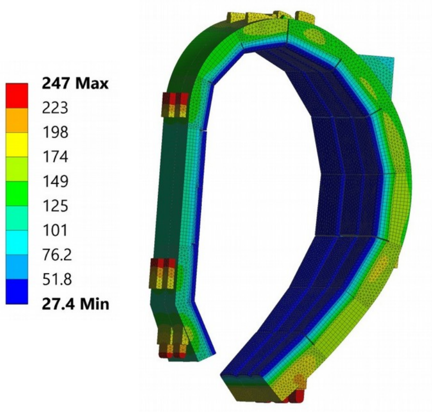
The first result is related to the natural convection applied only in BB plasma facing surfaces and the temperature result is reported in fig. 9. The internal surfaces can't be cool with the natural convection below the 100 °C threshold: the RM transporter tool support interface exhibits as highest value 165 °C.



(fig. 9: temperature contour plot with natural convection (°C))

When natural convection is applied also in the external surfaces of the BSS, the result in the support regions is practically the same: the lowest value in this case is 157 °C (not shown).

A different result has been obtained considering the forced convection with the parameters reported in tab. 1. Firstly, like in the previous case, the convection has been simulated only on BB plasma facing surfaces and the final result has been reported in fig. 10.



(fig. 10: temperature contour plot with forced convection (°C))

In this case the final temperature values obtained in the same points mentioned above are better than the previous case (the temperature values of the supports RME transporter tool range from 90 °C to 110 °C (not shown).

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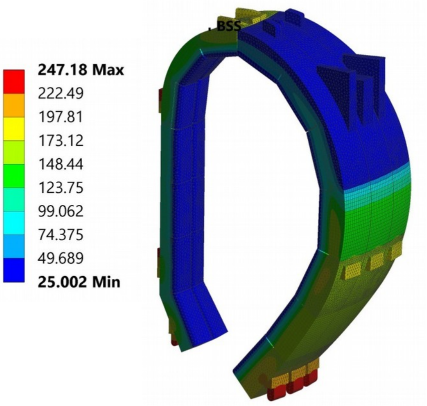
When the forced convection is applied also in the BSS external surfaces in front of the vacuum vessel upper port, the final temperature in these support points is lower of the highest value required and it reaches the imposed value by the cooling fluid as it can be seen in fig. 11.



(fig. 11: temperature result with forced convection acting also in the external BSS surfaces)

This last case answers to the initial question: the dedicated cooling system seems to be necessary in the viewing plasma surfaces that are the hottest ones and in the backside where the manipulator is called to operate. At the end of the analysis it can be stated that the forced convection must be adopted as with natural convection neither the upper temperature exercise limit of usual COTS technology seems to be assured (60 – 120 °C), while with the forced convection the support points temperature of the transporter tool is inside the mentioned range (also lower than the minimum in one case).

Comparing all the cases analysed, the connections (contact/target elements with always bonded option) between the BB modules backwall and the BSS external surfaces aren't able to conduct so much thermal energy: indeed when it is dealing with natural convection the plasma viewing surfaces remain hot without any relevant energy conduction towards the backside of the BSS that is at far lower temperature; more when it is dealing with forced convection the cold region produced by the convection load applied on the same plasma viewing surfaces isn't be able to enlarge towards the same backside of the BSS for the same thermal resistance offered by the small contact areas. Even though this result has been obtained in the simplified CAD model, it can be used as a guideline to plan the operations of the RHE during blanket maintenance and refurbishment.

4. Conclusions

The temperature evaluation during shutdown in the blanket zone where the transporter tool must be placed has been performed in two cases: natural and forced convection. The assumptions made in the natural convection (fixed temperature between BSS and VV etc.) and the limit of the geometrical model (one blanket sector, no upper port structure etc.) must be validated before a final conclusion: it will be drawn with the support of 3D CFD analyses.

The simulation has considered a blanket modules division and a blanket sector back supporting plate partition that could accomplish the form in which the decay heat data have been supplied.

The decay heat distribution has been considered for each segmentation either for the BB modules or for the parts in which the BSS has been divided; for what concerns the material properties, a suitable mixture of material properties has been adopted for the breeding zone and also voids have been taken into account.

The natural convection case shows final temperature (about 160 °C) that doesn't meet the requirement of standard COTS technology.

It must be highlighted that the final value of about 160 °C has been obtained assuming for the blanket backside bulk air temperature a "neutral" value of 150 °C (that is an average value between the central plasma region value and the surface vacuum vessel value): this choice can result a little arbitrary and further investigations can be carried on to keep out a strong link between the average value of the blanket backside bulk air temperature and the blanket lifting point final temperature.

The simulation related to forced convection shows final temperature of 25°C (when the forced convection interests all "opened" surfaces) that satisfies the admissible range (60-120°C) and the related components features verify the standard technology requirements.

The adoption of forced convection seems to be necessary thus determining a more demanding cooling system design.

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