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Progress on performances of Helium Cooled Molten Lead Ceramic Breeder, as a near-term alternative blanket for EU-DEMO

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Within the framework of EUROfusion activities, an alternative Helium Cooled Molten Lead Ceramic Breeder (hereafter called MLCB) solid breeder blanket is being also developed at KIT for European DEMO. This concept is proposed as an alternative near-term breeding blanket and it is based on a fission-like "fuel-breeder pin" configuration. Molten lead is used here as the neutron multiplier, Lithium-ceramics in form of pebbles inside the fuel-breeder pins as tritium breeder and pressurized helium as coolant. In comparison to typical former cooling-plate configurations, the fuel-breeder pin assemblies greatly reduce the pressure drop, potentially solving the key technology readiness issue of the currently available helium-circulator. In addition, the combination of lead and lithium ceramics shows a good tritium breeding ratio performance in a compact configuration (outboard blanket average radial thickness of 1000 mm instead of former 1300 mm).

After initial design studies with this concept for the previous EU DEMO baseline design (EU DEMO BL2015), the status of the conceptual design activities on the MLCB integrated in the latest EU DEMO baseline design (EU DEMO BL2017) are presented and discussed in this paper.

First, neutronics analysis has been performed to assess the soundness of the design in terms of tritium breeding ratio (a main design driver). Then, structural integrity of the preliminary blanket design under an in-box LOCA event (another design driver) has been assessed and the design is iterated to fulfill the design criteria. Thereafter, thermo-hydraulic analyses have been conducted to evaluate the blanket temperatures and the coolant pressure drop. After several design iterations to satisfy the temperature design limits and pressure drop requirements, a structural assessment under normal conditions has been conducted with respect to the structural design standard RCC-MRx. The results presented here show that the current design of the MLCB meets the basic nuclear and thermo-mechanic-hydraulic requirements, setting the path for a consolidated design of this concept.

Keywords: DEMO, Breeding Blanket, thermo-hydraulic analysis, thermo-mechanical analysis

1. Introduction

Within the framework of EUROfusion Breeding Blanket Project, Karlsruhe Institute of Technology (KIT) is currently in charge of developing the Helium Cooled Pebble Bed (HCPB) breeding blanket (BB) for the European DEMO [1]. Additionally, within the same project, KIT has also been developing an alternative near-term solid breeder BB called Helium Cooled Molten Lead Ceramic Breeder (hereafter called MLCB) [2]. After a comprehensive review of options for tritium breeder and neutron multiplier materials for breeding blankets [3], the element lead is selected as neutron multiplier. This concept uses stagnant molten lead instead of beryllium-contained material as neutron multiplier, which on one hand may compromise the neutron multiplying performance; on the other hand avoiding the use of beryllium-contained material solves the potential beryllium-related issues (e.g. toxicity, natural availability, uranium impurities and their transmutation under irradiation). Advanced lithium-contained ceramic breeder (ACB) pebbles (mixture of Li_4SiO_4 and Li_2TiO_3) with improved mechanical properties have been used as tritium breeder [4]. Pressurized helium gas is used as the coolant, EUORFER steel as structural material. Over the past years the helium cooled solid breeder blanket concept has used the breeder unit concept based on the use of the cooling plate with small cooling channels [1][5][6][7][8][9][10], that leads to a high pressure drop and respectively high circulating power of the helium coolant. In order to decrease the pressure drop, a new configuration is adopted that utilizes the fission-like fuel-breeder pin concept similar to the enhanced HCPB BB [11]. In comparison to the former HCPB cooling-plate configuration, the fuel-breeder pin design greatly reduces the pressure drop thanks to larger cooling channels in the breeder zone reducing the coolant velocity. This potentially reduces the circulating power to the level where state-of-the-art helium blower can be used. Furthermore, the fuel-breeder pin concept is easier and cheaper for fabrication. A dedicated mock-up of fuel-breeder pin has successfully been fabricated at KIT and has demonstrated to fulfill all design requirements [12]. The status of the manufacturing activity of the helium cooled First Wall developed at KIT is reported in [13].

2. Design description of MLCB

2.1 Basic configuration

The basic MLCB blanket configuration, integrated in the current EU DEMO baseline design (EU DEMO BL2017) [14][15], is shown in **Fig. 1**. In the current MLCB blanket concept the Single Module Segment (SMS) is used instead of Multiple Module Segment (MMS) used in the previous studies [1][16][17][18]. The

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blanket structure is built with the U-shaped first wall (FW), backplate of the breeder zone (BZ) and the back supporting structure (BSS). According to FW protection strategies for EU DEMO, a rooftop-shaped FW is needed to mitigate fusion plasma transient effects [19]. A 2 mm thick protecting layer of tungsten is used as the FW armor. The SMS segmentation not only facilitates the filling and draining of the molten lead, but also increases the tritium breeding performance. The fuel-breeder pin concept utilized in the present design includes two concentric tubes forming the cladding of the lithium ceramic pebbles: a small one (Φ_{OD}: 24 mm, thickness: 6 mm) and a large one (Φ_{OD}: 68 mm, thickness: 2 mm). At one side a "bell-mouth" funnel connects the two tubes. The breeder pins are arranged in the blanket in the radially oriented hexagonal lattice. The pitch of 125 mm between pins was found optimized to show the maximum tritium breeding performances of the blanket. The space between the tubes is used for placing of the lithium ceramic pebbles. Outside these tubes there is a larger concentric pressure tube (Φ_{OD}: 82 mm, thickness: 4 mm), forming the annular cooling channel together with the cladding. The coolant goes firstly through the small central tube, and then through the bell-mouth funnel turns into the annular channel. The molten lead fills the space between pins providing efficient neutron multiplication.

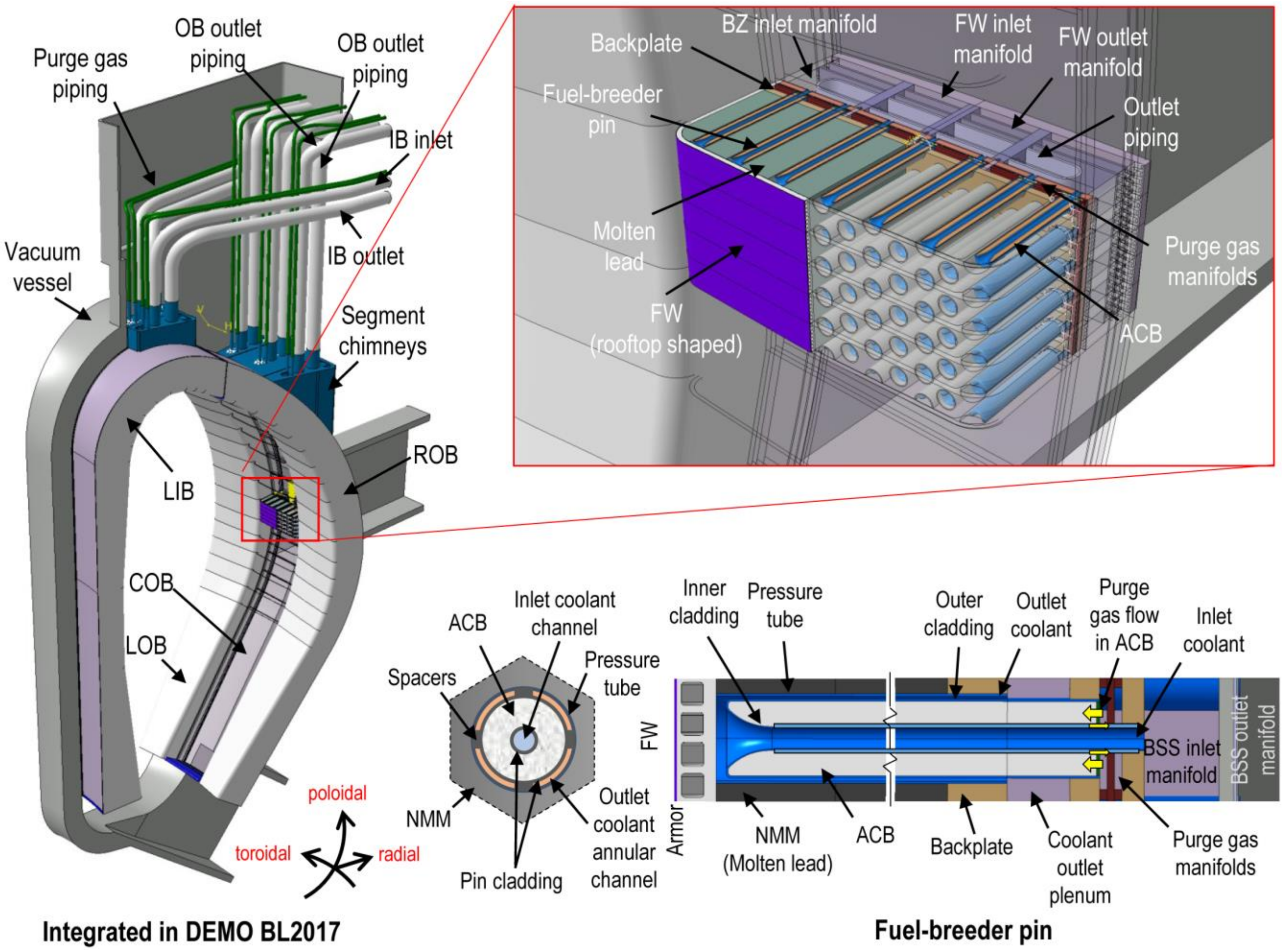

Fig. 1 MLCB integrated in EU DEMO BL2017 sector

2.2 Flow scheme

The schematic coolant flow scheme of the MLCB blanket is shown in **Fig. 2**. The neighboring FW built-in channels are cooled in a counter flow manner to homogenize the temperature distribution. The helium coolant at temperature of 300 °C with 8 MPa pressure is firstly flowing from FW manifold 1 (MF-1) and manifold 3 (MF-3). The helium is then collected and mixed in manifold 5 (MF-5). Thereafter the mixed coolant is distributed into the breeder zone (BZ) to remove heat generated in BZ. Finally the coolant is collected at manifold 6 (MF-6) with an expected mixed temperature of 520 °C. The space between MF-1 and MF-4, MF2 and MF-3, MF-5 and MF-6 is filled with insulated gas to prevent the heat exchange from each other. Because of the poloidal distribution of the heat loads coming from plasma [19], the FW cooling requirements are different at various poloidal positions. Close to the X-points where particles strike harder, the FW will suffer a peak heat load resulting in a high FW outlet temperature (assuming the FW channel sizes, inlet mass flow rate and temperature are the same with that of other positions). The FW outlet coolant from different poloidal positions is mixed to have a temperature of about 370 °C. The mixed coolant is then flowing into the BZ. This enables the reliable cooling of the BZ in different poloidal locations.

As discussed in [20] the shell-and-tube intermediate heat exchangers (IHXs) for the helium cooled DEMO could be very large due to the relatively low heat transfer coefficients of primary coolant helium and secondary coolant HITEC molten salt and the relatively small temperature differences between helium and HITEC molten salt. According to the equation $Q=h*\Delta T_{1,2}*A$ (here Q is the thermal power, h the heat transfer coefficient, $\Delta T_{1,2}$ the temperature difference between two fluids, A the heat transfer area), the required A can be decreased by increasing of h or/and $\Delta T_{1,2}$. Since increasing of h might cause the increase of pressure drop, it is more preferable to increase $\Delta T_{1,2}$ by increasing the blanket outlet temperature to 520 °C instead of the typical 500 °C for helium cooled blanket [1][2][5][6][7][8][21].

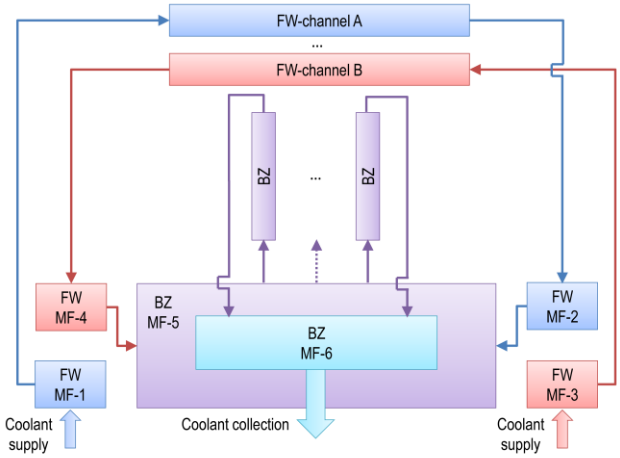

Fig. 2 Schematic flow scheme of the current MLCB

The blanket inlet temperature of 300 °C is chosen as a standard option. Based on the equation $Q=cp*m*\Delta T$ (here cp is the specific heat capacity, m the mass flow rate, ΔT difference between outlet and inlet temperature), for a given thermal power we can decrease the mass flow rate by increasing the outlet/inlet temperature difference (therefore decreasing pressure drop, since pressure drop is roughly proportional to m^2). The design with a higher blanket outlet temperature will also offer the potential to increase the net efficiency of the DEMO plant.

The neutronics, thermo-hydraulic and thermo-mechanical performance analyses are presented in the following sections.

3. Performance analysis

3.1 Neutronics analysis

The EU DEMO must demonstrate a reliable self-sufficient tritium breeding performance [14]. According to the European DEMO neutronics expert panel [22], the TBR design target of the breeding blanket shall be no less than 1.10. To assess the tritium breeding capability of the newly developed MLCB blanket, rigorous neutronics analyses have been performed making use of a detailed 3D heterogeneous MCNP geometry model. This model was produced using a consistent integral approach including automated conversion procedure based on the McCad conversion tool [23] developed at KIT. In order to improve the plasma vertical stability, in the current EU DEMO baseline (EU DEMO BL2017) the maximal radial thickness of BB in the outboard side has been decreased from 1300 mm to 1000 mm [15]. The BZ dimensions are presented in section 2.1, the maximal BZ radial thickness is of 380 and 610 mm for inboard and outboard blanket. The 90% ^{6}Li enrichment has been used in the calculations [24]. Within this compact configuration, after several design iterations the MLCB DEMO shows a TBR of 1.13 taking into account the reduction effect of rooftop-shaped FW (-0.03) and bending of FW (-0.01). That means TBR will become 1.17 if not taking into account the effect of rooftop-shape and bending of FW [24]. The nuclear heating (which is needed for thermo-hydraulic calculations) generated in different materials at the typical outboard equatorial midplane are presented in **Fig. 3**.

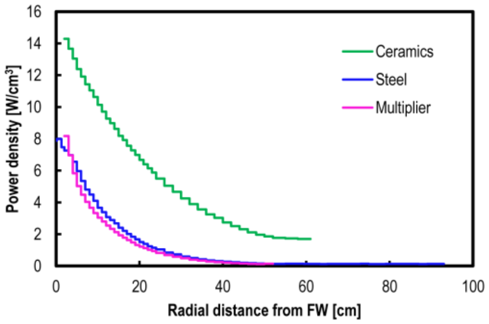

Fig. 3 Power densities of different materials

3.2 Thermo-mechanical analysis under in-box LOCA

During the course of the BB development over the past years, the in-box LOCA (Loss Of Coolant Accident within blanket box) has been identified as one of the key design drivers for breeding blanket [1][18]. The optimization and analysis process of the previous MLCB blanket [2] show that the critical parts are located at the back supporting structure (BSS). Therefore, in-box LOCA thermo-mechanical study was firstly focused on the optimization of BSS. To get quick feedback from thermo-mechanical analysis, only BSS with primary loading (with 8MPa+about 20% pressure applied on the surfaces in contact with coolant and the purge gas) was considered in the calculations. The geometry modification is presented in **Fig. 4**. After several design iterations, the version 2 (v2) with robust mechanical performance has been chosen as the reference BSS geometry.

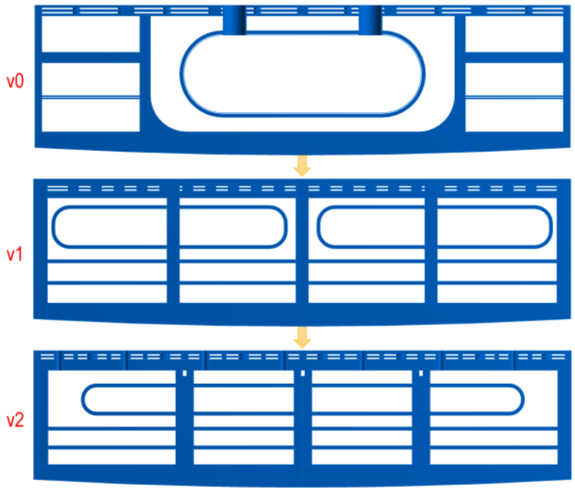

Fig. 4 Design iterations of BSS

The thermal and thermo-mechanical analyses were performed by using the Finite Element Method (FEM) software ANSYS. It is obviously shown from **Fig. 1** that in the poloidal direction the fuel-breeder pins are repeatedly arranged. To save meshing and computing time, a representative toroidal-radial unit slice located at outboard equatorial midplane is used. This unit slice model includes 14 halves of fuel-breeder pins and the corresponding slice of molten lead, FW and BSS.

The mechanical integrity of the blanket under in-box LOCA has been then assessed with regard to damage modes induced by primary stresses. The blanket box is pressurized with 10 MPa (8 MPa normal pressure + ~20% uncertainties). The linearization of primary stresses (see **Fig. 5**) on the blanket structure is then performed at critical regions (regions A, B, C at **Fig. 5**) according to on the specified paths, showing global fulfillment of RCC-MRx rules under level D criteria.

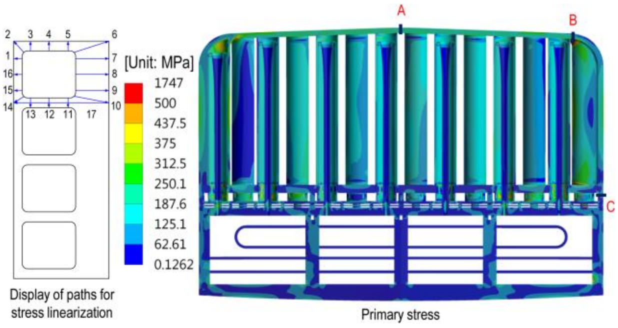

Fig. 5 Primary stress under in-box LOCA

3.3 Thermo-hydraulic analysis

According to the energy conservation law, the mass flow rate for one fuel-breeder pin at outboard equatorial midplane is about 15.6 g/s. The heat transfer coefficient (HTC) for the pin channels have been calculated by Bhatti-Shah correlation [25]. The normal roughness of 6.8 μm has been applied to the central pin inlet channels. On the pin outlet annular channels a typical roughness of 44 μm has been implemented to enhance the heat transfer because the relatively low-pressure drop achieved in the design enables application of such parameter. The resulting average HTCs for the pin inlet and outlet channels are about 3100 and ~1570 W/(m²·°C) respectively.

With power density profiles discussed above and appropriate boundary conditions, the optimized temperature distribution of the unit slice of MLCB blanket has been obtained by ANSYS calculations, see **Fig. 6**. The maximum temperatures are 822.8, 550.9 and 627.6 °C for ACB, EUROFER and molten lead respectively. The minimum temperature of molten lead is 357.6 °C, which is above the lead melting point of 327.5 °C at normal atmospheric pressure. The temperatures of functional materials are within corresponding design limits. The maximum temperature on EUROFER steel is about 551 °C, the minimum one is 300 °C, which is not a critical issue as long as the stresses at the region fulfil the RCC-MRx rules (as shown below by the thermo-mechanical analysis). The mixed outlet temperature of the helium coolant is about 520 °C.

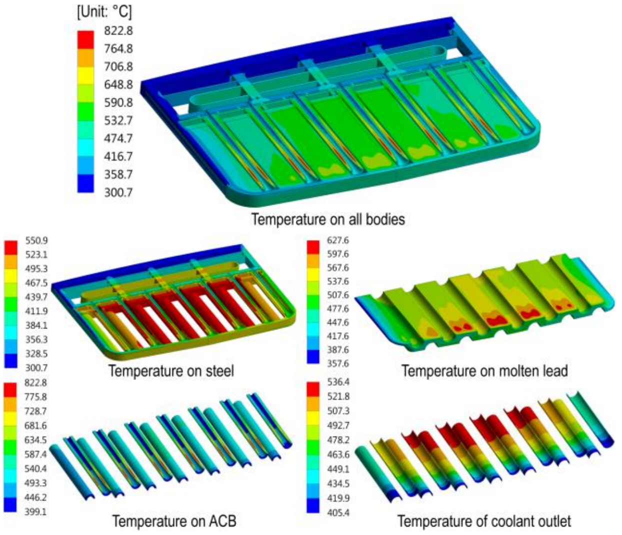

Fig. 6 Temperature distribution of typical MLCB unit slice

According to the neutronics analysis [24], the total thermal power generated in all MLCB DEMO blankets including surface heat flux is about 1964 MW. With an outlet temperature of 520 °C the total helium mass flow rate for the MLCB blanket is about 1718 kg/s (1890 kg/s if outlet temperature is 500 °C). Full-scale CFD calculations (Streamline at outboard BZ outlet manifold is shown in **Fig. 7**) have been performed for the BSS manifolds, showing 0.066 and 0.091 MPa pressure drops for outboard and inboard BSS manifolds. The pressure drops for outboard and inboard FW and BZ channels are respectively about 0.024 and 0.02 MPa. The pressure drop for the piping and other components of the helium Primary Heat Transfer System (PHTS) is about 0.1÷0.2 MPa. Roughly, a circulating power of about 39.6÷60.4 MW is obtained for outboard side, 11÷16.2 MW for inboard side. Assuming 16 helium circulators (previously 18 circulators [20]) in the PHTS, each circulator provides 3.2~4.8 MW of circulating power, which is achievable based on existing helium blower technology [26].

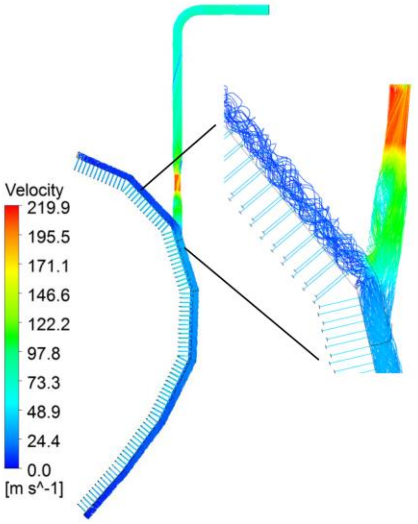

Fig. 7 Streamline at outboard BZ outlet manifold

3.4 Thermo-mechanical analysis under normal conditions

The stress calculations under normal conditions have taken into account the primary stresses and secondary stresses. The temperature distributions are taken from the analysis from section 3.3. All the surfaces contacting helium coolant have 8 MPa and all the surfaces contacting purge gas have 0.2 MPa gas pressure.

At the bottom surface of the unit slice a symmetry condition has been imposed while at top surface a parallel motion with respect to the bottom surface of the unit slice has been applied.

Firstly the calculation of primary stresses have been performed considering here the pressure loads. Secondly the primary (P) plus secondary (Q) stresses (here mainly the thermal stresses) have calculated by applying both pressure and thermal loads.

The primary plus secondary stresses contour is shown in **Fig. 8**. Stress linearization assessment has been performed with regard to RCC-MRx rules at level A criteria. At the critical regions, comprehensive paths are used, like the paths shown in **Fig. 5** left. The current design shows a robust global structural performance. The FW, BZ and BSS fulfill immediate plastic collapse (IPC), immediate plastic instability (IPI), immediate plastic flow localization (IPFL) and thermal creep damage modes. While the regions connecting the BZ and BSS fail to meet the criteria of the IPFL damage mode due to large thermal gradient between the hot BZ and the cold BSS structure (See the temperature distribution in **Fig. 6**). Further design improvement leading to decrease the thermal gradient between both sides should be implemented.

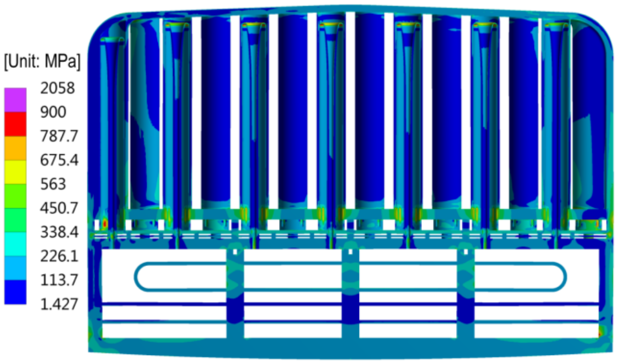

Fig. 8 P+Q stresses of typical MLCB unit slice

4. Conclusions

In this paper, the basic structural and thermal hydraulic schemes of the newly proposed Helium Cooled Molten Lead Ceramic Breeder breeding blanket have been briefly described. Due to the very promising features of the present design such as low pressure drop, easy fabrication procedure and great abundance of lead the present MLCB blanket concept seems to be an attractive near-term alternative strategy for the EU DEMO developed within the EUROfusion Breeding Blanket Project. The promising nuclear, thermo-hydraulic and thermo-mechanical performances of the current design have been reported. The results show that the current design of the MLCB meets the basic nuclear and thermo-mechanic-hydraulic requirements, setting the path for a consolidated design of this concept.

Acknowledgments

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