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Progress in the design development of EU DEMO Helium-Cooled Pebble Bed Primary Heat Transfer System

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In the frame of the activities promoted and encouraged by the EURO-fusion Power Plant Physics and Technology (PPPT) department aimed at developing the EU-DEMO fusion reactor, strong emphasis has been recently posed to the whole Balance of Plant (BoP) which represents the set of systems devoted to convert the plasma generated thermal power into electricity and to deliver it to the grid. Among these systems, a very important role is played by the Breeding Blanket (BB) Primary Heat Transfer System (PHTS) as it is responsible to extract more than 80% of the fusion plasma power.

In this framework, University of Palermo, Ansaldo Nucleare and CREATE have focused their work to improve thermal-hydraulic, safety and integration features of the Ex-Vessel PHTS for the Helium-Cooled Pebble Bed (HCPB) BB concept of DEMO.

Starting from the outcomes obtained last year that have allowed to highlight some criticalities which needed design changes, the paper describes progress and developments of the HCPB PHTS as well as the goals which have been achieved. The results of the research activity carried out show, in fact, an overall increase of both safety characteristics and thermal-hydraulic performances since a reduction in total coolant inventory and total pressure drop has been respectively reached. Nevertheless a critical assessment of these key parameters reveals that some issues are still open in terms of design integration and feasibility of the whole DEMO BoP for the helium-cooled blanket option, indicating that additional efforts are required to make this technology more attractive.

Keywords: DEMO, Balance of Plant, PHTS, HCPB.

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1. Introduction

The EU-DEMO conceptual design is being conducted among research institutions and universities from 26 countries of European Union, Switzerland and Ukraine. Its mission is to realize electricity from nuclear fusion reaction by 2050. The recent European roadmap, has established that several hundred MW of electricity must be produced by DEMO plant which has to ensure an adequate availability and reliability of operation over a reasonable time span [1],[2]. Due to this reason the EU-DEMO plant design has to be strongly oriented to the Balance of Plant (BoP).

The BoP in fact is made up of all those systems which scope is to convert the fusion power into electricity, the electrical power supply, the cryogenic plant and several auxiliaries providing specific fluids and gases to various apparatus according to their need [3].

The systems that are the core of the DEMO BoP, since they represent the fundamental energy "chain", being devoted to the extraction of the plasma generated thermal power and to its conversion into electricity delivered to the grid, are the Primary Heat Transfer Systems (PHTSs) of Breeding Blanket (BB), Divertor (Div) and Vacuum Vessel (VV), the Intermediate Heat Transfer System (IHTS) and the Power Conversion System (PCS) [4][5], Fig 1. In particular, since the BB has to extract about 85% of the power generated by the tokamak, hence it might be intended as the main hub of the heat transfer chain.

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Starting from the outcomes obtained during the 2016 activities which highlighted some criticalities that needed design changes [4][5], the paper describes progress and developments of the HCPB BB PHTS as well as the goals which have been achieved. The results of the research activity carried out show, in fact, an overall increase of both safety characteristics and thermal-hydraulic performances since a reduction in total coolant inventory and total pressure drop has been respectively reached. Nevertheless a critical assessment of these key parameters reveals that some issues are still open in terms of design integration and feasibility of the whole DEMO BoP for the helium-cooled blanket option, indicating that additional efforts are required to increase the overall performances of the system.

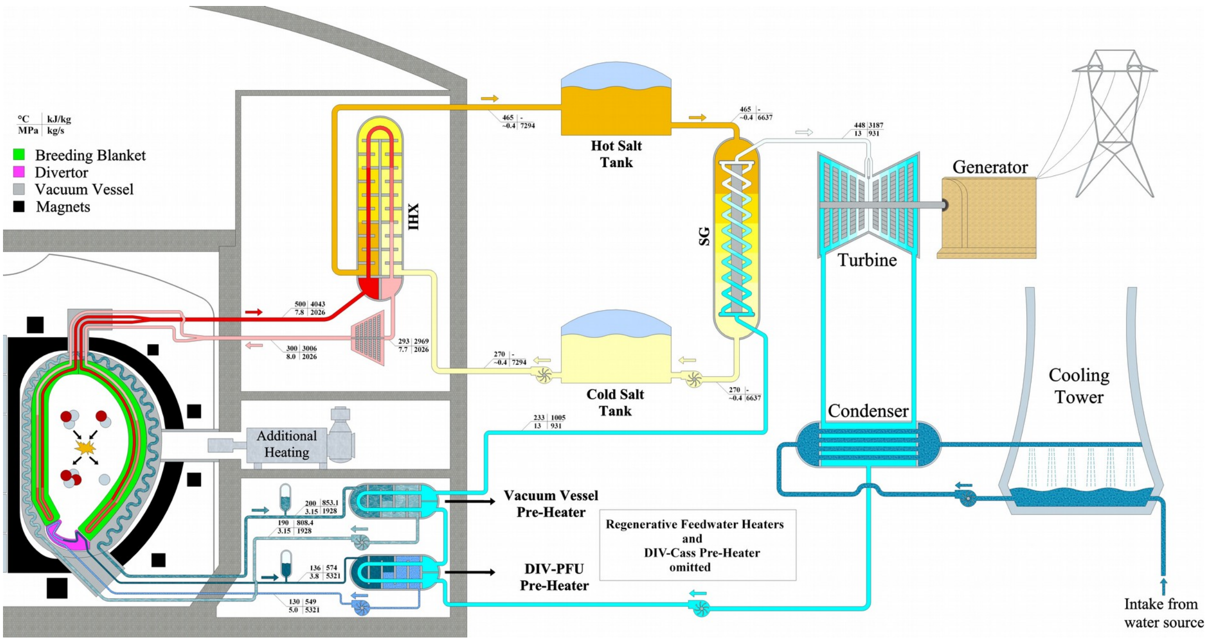

Fig. 1. Conceptual scheme of helium-cooled BB BoP with ESS.

2. HCPB BB PHTS design description

2.1 Current BB architecture

The current HCPB BB PHTS is designed to fulfil requirements and constrains dictated by the so-called "sandwich" concept [6], developed for the EU DEMO 2015 tokamak baseline [7], where the blanket is subdivided in 18 sectors, each one of 20°. A sector includes two Inboard Blanket (IB) segments and three Outboard Blanket (OB) segments. An IB/OB segment is subdivided in seven blanket boxes, following a multi-module structure where First-Wall (FW) and Breeding Zone (BZ) cooling channels are housed [8]. Fig 2 depicts a HCPB sectors and its equatorial module.

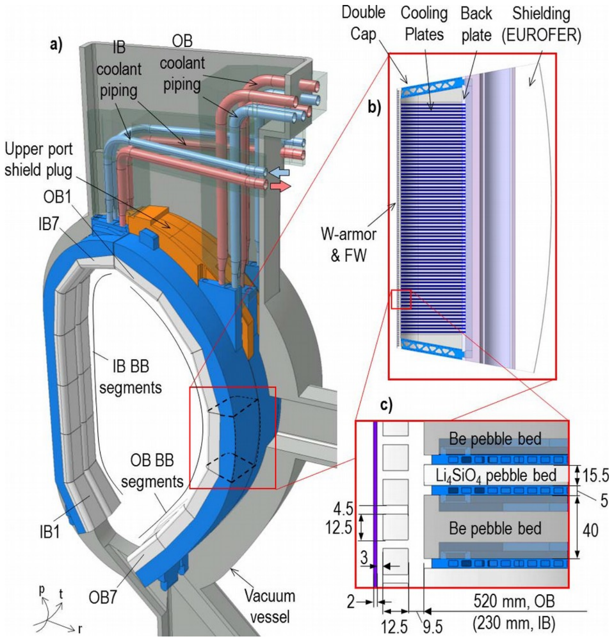

Fig. 2. HCPB BL2015. (a) HCPB DEMO sector. (b) Section cut of the OB4 module. (c) Detail of the BZ. Coordinates: p = poloidal, t = toroidal, r = radial.

2.1.1 BB flow scheme and thermal-hydraulic conditions

Each module is made up of a recurring sub-structure where helium at 8 MPa and 300°C coming from the inlet manifold enters, cools in series FW and BZ and, finally, reaches the outlet manifold at 500 °C [8]. A "1-side bottom-top" arrangement is currently selected to route the Ex-Vessel cooling pipes to the In-Vessel components: inlet and outlet pipes are all routed through the upper port reducing the integration problems identified for the BoP with the former "2-side bottom-top" arrangement [4] as well as decreasing the complexity of Remote Maintenance operations [9].

The relatively narrow working window of the coolant (300÷500 °C) is dictated by the lower and upper design limits of the low activation structural steel EUROFER which is affected by irradiation hardening and embrittlement as well as reduction in fracture toughness at temperature below 350 °C whereas helium embrittlement and reduction in fatigue life becomes significant above 550 °C. To be compliant with such BB requirements a helium total mass flowrate of 2025.7 kg/s must be circulated through the whole PHTS in order to remove from the BB a nominal thermal power of 2101.7 MW.

2.2 Ex-Vessel PHTS design

The present Ex-Vessel PHTS has been developed on the basis of the preliminary studies carried out during the 2016 BoP activities and following the same strategies and objectives which had driven the previous design [4] [5].

2.2.1 PHTS layout

The BB PHTS architecture still relies on the adoption of 9 completely independent cooling loops from both mechanical and functional point of view in order to limit some common mode failures. The IB is cooled by means of 3 loops whereas the remaining 6 circuits are employed to remove the thermal power from the OB portion of the tokamak. An IB loop is responsible for providing helium to 6 blanket sectors while an OB loop cools the segments of 3 blanket sectors. Fig. 3 shows the 3D-CAD model of the 2017 HCPB BB PHTS.

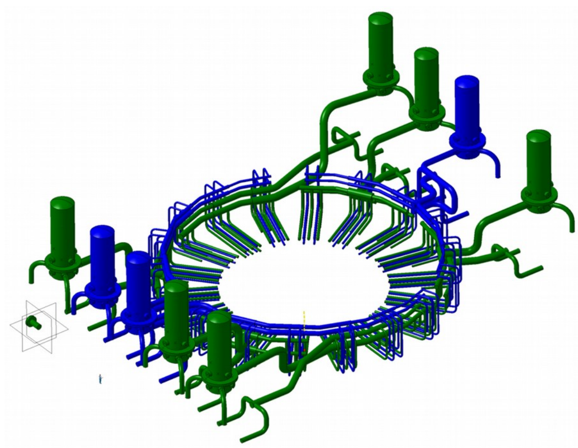

Fig. 3. 3D view of HCPB BB PHTS cooling loops.

The choice to maintain a high degree of loops segmentation is due to the necessity of limiting the potential consequences of some LOCA events and keeping the dimensions of main PHTS equipment within reasonable and feasible sizes.

However, a careful review of analyses performed on the preliminary BB PHTS layout [10][11][12] highlighted criticalities which were mostly related to the huge number of pipes employed and, consequently, to their excessive overall length: hundreds of components and several kilometres of piping with their thousands of welding clearly increase the possibility of the system to fail compromising reliability, availability and safety of the whole plant. Moreover, a tokamak building crowed of high energy pipes carrying radioactive materials among different levels of the structure might generate several integration, maintenance and, again, safety problems.

For abovementioned reasons it was decided to make important modifications to the design and layout of the pipework that is now placed at the height of the upper ports since BB inlet/outlet pipes interface at that level. In addition, even if the flow scheme described in [4] was kept unchanged as well as the structural material, namely AISI 316L(N), a single larger pipe has replaced the three parallel pipes which formerly connected the Intermediate Heat eXchanger (IHX) to the BB manifolds on both cold and hot sides. These changes have allowed to strongly reduce the number of pipes, see Table 1, and their total length which was more than halved respect to the previous design being around 4 km; as directly consequence, also the coolant volume decreased to 879 cubic meters, with a gain of about 33%.

On the other hand, the adoption of single hot/cold leg which nominal diameter is DN1300 and DN1100, respectively, will require additional efforts in the manufacturing process taking into account the related increment of pipes thickness (up to 65 mm for the hot leg). Nevertheless, this option seems doable as many factories on the market offer pipes of the required sizes guaranteeing nuclear quality standards [13].

Table 1. 2017 HCPB PHTS main components per loop.

Component	Inboard	Outboard
Hot/Cold manifolds	12/12	9/9
Hot/Cold legs	1/1	1/1
Cold Header	1	1
Compressors	2	2
Heat exchanger	1	1

2.2.2 Intermediate heat exchanger

The IHX has similar features to the previous model [4] since the adoption of equipment widely used in nuclear and conventional industrial applications, therefore easily available on the market, is one of the main drivers for the component selection. Therefore, the TEMA NFN type (two-pass tubes, two-pass shell) is the reference design configuration for the heat exchanger, where helium flows on tube side whereas the HITEC salt crosses the shell side. Fig. 4 shows a conceptual 3-D model of the OB IHX.

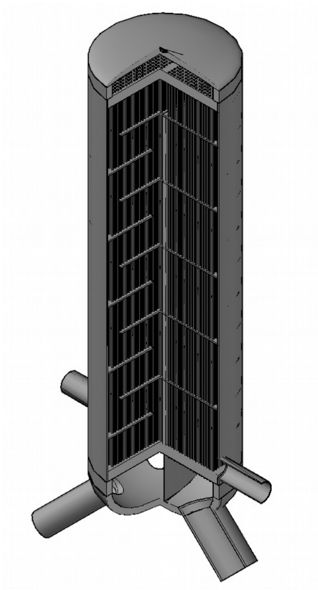

Fig. 4. 3D view of 2017 OB IHX.

Taking into account the results of the 2016, it was decided to increase the temperature difference between primary and secondary loops to reduce the overall dimensions of the component: the secondary cycle temperatures were set to 270 °C–465 °C (T_{in} and T_{out} respectively), according to [14]. As can be caught from the Table 2, the size of the IHX for both IB and OB loops, is considerably decreased.

Table 2. IHXs main data.

Parameter	IB	OB
Thermal Power [MW]	208.1	267.8
T_{in}/T_{out} helium [°C]	500.0/287.7	500.0/289.3
T_{in}/T_{out} HITEC salt [°C]	270.0/465.0	270.0/465.0
Bundle length [m]	12.2	11.6
No. of tubes (1 pass)[-]	5801	7426
Tube D_{ext} [mm]	19.05	19.05
He pressure drop [MPa]	87.9	85.1
Total He volume [m^3]	49.5	61.5

Moreover, this new HITEC thermal-hydraulic conditions allowed to decrease the component pressure drop of about 26%-28%, for IB and OB IHX respectively.

Nevertheless, the total heat transfer area of about 87300 m^2 poses questions regarding the tritium permeation through such a huge surface, revealing that additional efforts should be made to minimize this potential issue [15].

2.2.3 Pressure drop and pumping power

The improvements in both In-Vessel and Ex-Vessel components design had a very positive impact on the global pressure drop of the BB PHTS. However the circulators power, see Table 3, is still high respect to the value of 5 MW per compressor previously foresaw in [4]. Further developments of the BB PHTS aimed ad optimize pressure losses of the whole cooling circuits are needed to achieve, or at least approach, such target value in order to avoid the necessity of large R&D campaigns.

Table 3. PHTS pressure drop and circulator power.

Parameter	IB	OB
In-VV ΔP [kPa]	214.0	174.0
Ex-VV piping ΔP [kPa]	62.0	56.6
IHX ΔP [kPa]	87.9	85.1
Circulator power [MW]	6.8	7.5

3 "Near-term" PHTS

The latest EU DEMO 2017 baseline foresees 16 VV sectors in place of 18, as it was in former baseline. This major modification, together with the need to improve the whole HCPB blanket system and its PHTS, has led to a design revision towards establishing a simpler, near-term blanket configuration. Such option is based on a fission-like hexagonal arrangement of radial fuel-breeder pin assemblies built in Single-Module Segments [16]. This new HCPB architecture shows enhanced thermal-hydraulic performances managing to reach higher helium outlet temperature (∼520°C) and, in the meanwhile, lower pressure drop. This has led to re-think the PHTS layout encouraging an options based on 8 homogeneous loops where each cooling circuit feeds both IB and OB segments of a VV sector allowing the adoption of the same equipment (e.g. IHX, circulator) in all loops. For the "near-term" HCPB BB PHTS two options of IHX are under investigation focusing on the "tubes and shell" heat exchanger technology: in particular, a "base" configuration foresees a common, easy-to-manufacture, once-through Shell&Tube HX (STHE) with a straight tube bundle, while an "advanced" option conceives the adoption of a Coil-Wound Heat Exchanger (CWHE) where tubes are wound into helical coils forming a large bundle. Preliminary studies have highlighted good capabilities of both options which virtually would enable the design of circulators which do not need large R&D to be build. The CWHE can ensure better thermal-hydraulic characteristics than STHE, however, even if such typology has been widely commercialized in both nuclear and fossil energy systems, analyses are on-going in order to understand whether this option suits requirements and constrains of DEMO BoP.

Table 4 summarizes the results of preliminary analyses carried out on pressure drops and pumping power for the two "near term" BB PHTS configurations.

Table 4. Near-term PHTS: pressure drop and circulator power.

Parameter	STHE		CWHE	
	IB	OB	IB	OB
In-VV ΔP [kPa]	156	107	156	107
Ex-VV piping ΔP [kPa]	44.6	93.6	44.6	93.6
IHX ΔP [kPa]	63.1		33.7	
Circulator power [MW]	5.9		5.2	

4. Conclusion

A new reference design for the HCPB BB PHTS has been outlined. Significant improvements have been achieved in term of reduction of HXs heat transfer area, piping length, coolant inventory and pumping power. The modifications of PHTS design have had a positive impact on both safety and integration characteristics of the system, virtually increasing its reliability and availability. However, further design refinements of equipment such as IHXs and circulators are needed to ensure the overall feasibility of a DEMO BoP based on helium technology.

An enhanced, near-term PHTS is under development for the new EU DEMO 2017 baseline. It is addressed at overtaking the low technology readiness issues, thus enabling the use of mature and well-known solutions for the main BoP components.

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