

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 in 2016 that have allowed to highlight some criticalities which needed design changes, the paper describes progress and developments of the 2017 HCPB PHTS as well as the goals which have been achieved. The results of the research activity carried out show, in fact, i) an increase of the thermal-hydraulic performances, since a reduction in both total coolant inventory and total pressure drop has been respectively reached, ii) a potential improvement of the overall safety characteristics of the system. 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.

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]. DEMO should be capable of operating with a closed fuel-cycle and to be a facilitating machine between ITER and a commercial fusion power plant.

In order to take a step toward a complete exploitation of the fusion power, DEMO must be equipped with all those systems designate to convert nuclear power into electricity. The part of the plant which scope is to allow this energy conversion is called Balance of Plant (BoP). Thus the main role of the BoP is to deliver electricity to the grid, however it has also to supply energies to many interfaces and auxiliary systems (e.g. the cryogenic plant) which are essential for the plant operation [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, 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, it might be intended as the main hub of the heat transfer chain.

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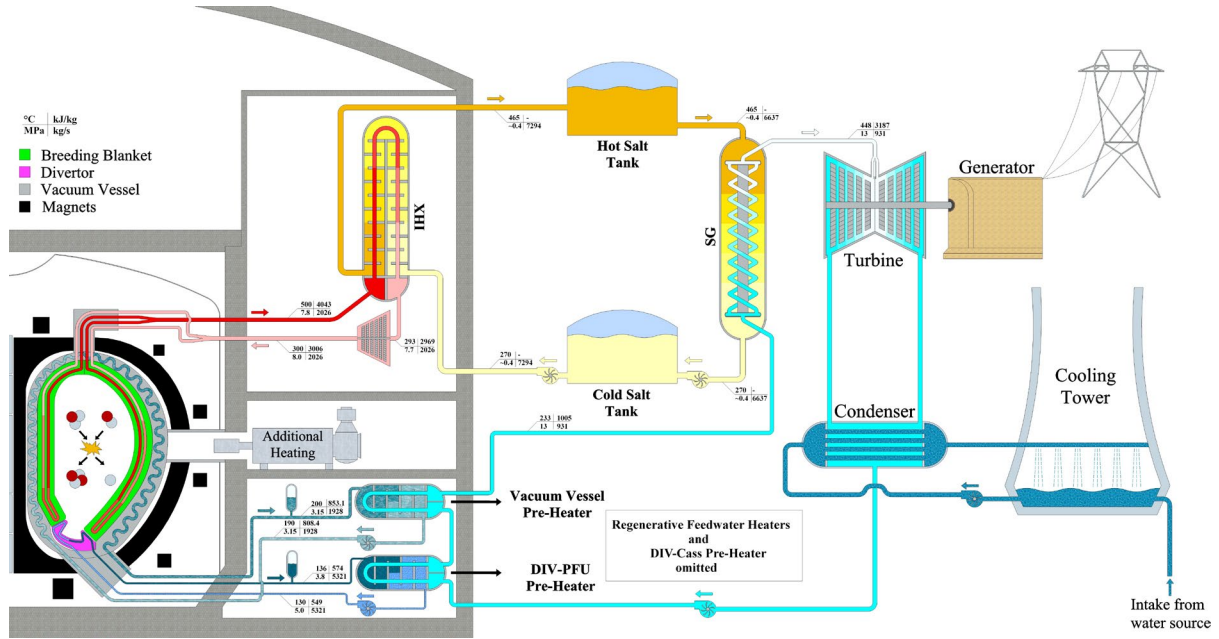


Fig. 1. Conceptual scheme of DEMO BoP for the helium-cooled breeding blanket option [5].

2. HCPB BB PHTS design description

2.1 Current BB architecture

The current 2017 HCPB BB PHTS is designed to fulfil requirements and constraints 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.

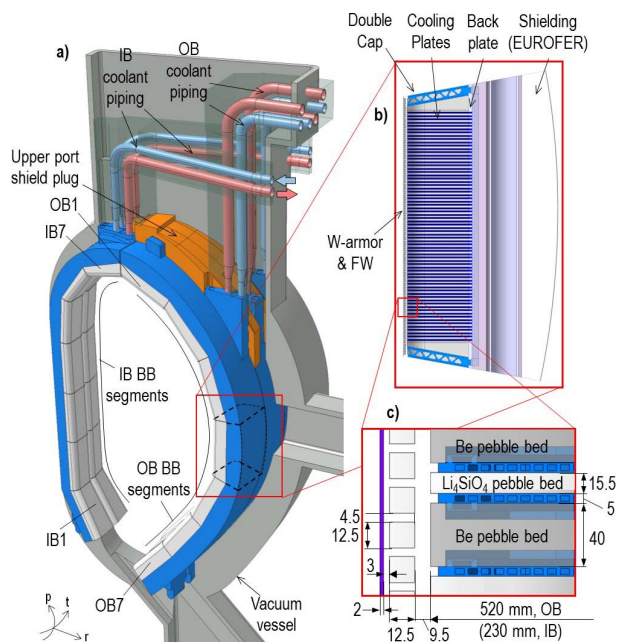


Fig. 2. HCPB BL2015. (a) HCPB DEMO sector. (b) Section cut of the OB4 module. (c) Detail of the BZ. Coordinates: p = poloidal, t = toroidal, r = radial.

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]. Furthermore, the adoption of a single inlet/outlet pipe to feed each segments has allowed to halved the number of feeding pipes respect to the previous design.

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]. The relevant data and the number of main components for the 2017 BB PHTS design are reported in Table 1 and Table 2, in comparison with the previous design values.

Table 1. 2017vs2016 HCPB BB PHTS main data.

Parameter	2017 PHTS	2016 PHTS
Thermal power [MW]	2101.7	2389.1
Circulator power [MW]	130.4	196.7
Coolant volume [m ³]	1976.4	2573.1
Piping length [m]	4002.8	8626.1
IB/OB cooling loops [-]	3/6	3/6

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.

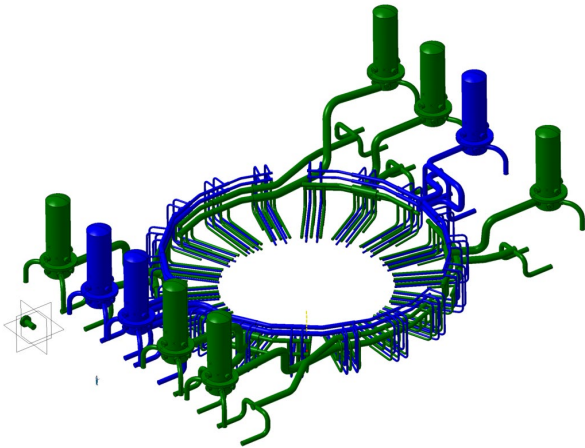


Fig. 3. 3D view of HCPB BB PHTS cooling loops.

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. In fact 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 of the whole plant as higher piping failure rate increases maintenance periods which require longer plant shut-down. Moreover, a tokamak building crowded of high energy pipes carrying radioactive materials among different levels of the structure might generate several integration and maintenance issues strongly related to the fulfilment of all safety requirement (e.g. difficulty of routing the pipes among different tokamak rooms and

levels taking into account the necessity of physical segregation between systems which have totally different functions to avoid knock on effects, huge work expected for the inspection of piping and welding) [13] [14].

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 cooling 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 2, 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 [15].

Table 2. 2017vs2016 HCPB BB PHTS component per loop.

Component	2017 PHTS		2016 PHTS	
	IB	OB	IB	OB
Hot/Cold manifolds	12/12	9/9	24/24	18/18
Hot/Cold legs	1/1	1/1	3/3	3/3
Cold Header	1	1	1	1
Compressors	2	2	2	2
Heat exchanger	1	1	1	1

2.2.2 Intermediate heat exchanger

The IHx, Fig. 4, 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.

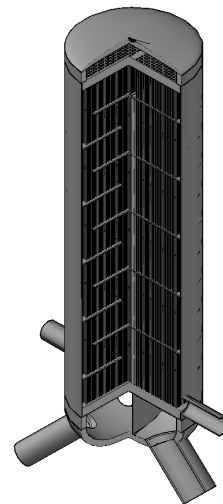


Fig. 4. 3D view of 2017 OB IHX.

Therefore, the TEMA BFM type (two-pass tubes, two-pass shell) is the reference design configuration for Table 3. IHXs main data.

Parameter	Base Case		2016 PHTS	
	IB	OB	IB	OB
Thermal Power [MW]	208.1	267.8	245.2	304.9
T_{in}/T_{out} helium [°C]	500.0/287.7	500.0/289.3	500.0/284.5	500.0/285.6
T_{in}/T_{out} HITEC salt [°C]	270.0/465.0	270.0/465.0	268.0/480.0	268.0/480.0
Tubes active length (per pass) [m]	12.2	11.6	17.0	16.5
Tube number (per pass) [-]	5801	7426	6779	8427
Tube external diameter [mm]	19.05	19.05	19.05	19.05
Helium pressure drop [kPa]	87.9	85.1	117.5	117.7
Total helium volume [m ³]	49.5	61.5	65.3	79.2

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 [16]. As can be caught from the Table 3, the size of the IHX for both IB and OB loops, is considerably decreased. Moreover, this new HITEC thermal-hydraulic conditions allowed to decrease the component pressure drop of about 26% and 28%, for IB and OB IHX respectively.

Nevertheless, the total heat transfer area of about 87300 m² poses questions regarding the tritium permeation through such a huge surface, revealing that additional efforts should be made to minimize this potential issue [17].

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 4, is still high respect to the value of 5 MW per compressor previously foresaw in [4]. Further developments of the BB PHTS aimed at 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 4. 2017 BB 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 [18]. This newest HCPB architecture which is being developed shows enhanced thermal-hydraulic performances managing to reach higher helium outlet

the heat exchanger, where helium flows on tube side whereas the HITEC salt crosses the shell side.

temperature (~520°C) and, in the meanwhile, lower pressure drop. Such improvements have suggested to re-think the PHTS layout during the 2018 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 5 summarizes the results of preliminary analyses carried out on pressure drops and pumping power for the two “near term” BB PHTS configurations.

Table 5. 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. Design changes of the PHTS have been also aimed at attaining an increase in 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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