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Preliminary Design of EU DEMO Helium-Cooled Breeding Blanket Primary Heat Transfer System

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The European DEMO conceptual design foresees four Breeding Blanket (BB) concepts that rely on different cooling and breeding technologies. As DEMO has been conceived to deliver net electricity to the grid, the choice of the blanket coolant plays a pivotal role in the reactor design having a strong influence on plant operation, safety and maintenance. Moreover, the machine pulsed operation makes the BB Primary Heat Transfer System (PHTS) the main hub of the DEMO Balance of Plant (BoP).

Within this framework, a study has been carried out to design the Ex-Vessel PHTS of the Helium-Cooled Pebble Bed (HCPB) BB concept.

The paper describes criteria and rationale followed with the aim to achieve a simple PHTS design based on the adoption of easy-to-manufacture main components. Results of preliminary thermal-hydraulic calculations carried out to size heat exchangers, piping and compressors are presented and critically discussed. Finally, the evaluation of PHTS key parameters as total pressure drops and total coolant inventory is reported to provide input relevant to the assessment of the impact of helium technology on the design integration and feasibility of DEMO BoP.

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

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1. Introduction

The recent European roadmap, drafted to realize commercially viable fusion power generation, has established that several hundred MW of electricity must be produced by DEMO plant which has to ensure an adequate availability/reliability operation over a reasonable time span [1,2]. For such reason the EU DEMO plant design has to be strongly oriented to the Balance of Plant (BoP) that includes several systems which, together, work to assure a reliable, safe and efficient operation of the machine.

The system that in many fission Nuclear Power Plants (NPPs) is traditionally the core of the BoP is the Power Conversion System (PCS), to which the thermal power is delivered by the Primary Heat Transfer System (PHTS) in order to be converted in mechanical and then into electrical power respectively by means of the turbine and the alternator. In DEMO, conversely, the pulsed nature of the heat source enhances the dependence of PCS operation on the Breeding Blanket (BB), Divertor (Div) and Vacuum Vessel (VV) PHTSs making them central actors of the BoP.

In particular, since the BB has to extract about 85% of the power generated by the tokamak and its conceptual design foresees four concepts that rely on different cooling and breeding technologies, it may be considered as the main hub of the DEMO BoP.

Moreover, with the aim of mitigating the potential negative impact of plasma pulsing on the turbine and the PCS equipment, for the DEMO plant is being investigate a "heat transfer chain", Fig.1, option which foresees the use of an Intermediate Heat Transfer System (IHTS) that should act as bridge from the BB PHTS to the PCS. Such intermediate system is equipped with an Energy Storage System (ESS) that, during the pulsed operation, collects a portion of the thermal energy transferred by the blanket in order to give it to the PCS during the dwell time; this device should therefore limit sharp changes in turbine load let it to work in pseudo steady-state condition both during pulse and dwell time.

Within this framework, one of the activities on the DEMO BoP developed at the University of Palermo in agreement with the Ansaldo Nucleare and the EUROfusion Programme Management Unit (PMU) has been focused on the assessment and preliminary design of the EU DEMO Helium-Cooled BB PHTS. The paper describes criteria and rationale followed with the aim to achieve a simple PHTS design based on the adoption of easy-to-manufacture main components. Results of preliminary thermal-hydraulic calculations carried out to size heat exchangers, piping and compressors are presented and critically discussed.

The main Ex-Vessel PHTS components have been sized to be compliant with the thermal-hydraulic and geometrical requirements of the Helium-Cooled Pebble Bed (HCBP) BB concept. However, even if numerical data (i.e power input, pressure drops, etc.) will be referred to such concept, all the general considerations made for the design of helium components and most of the results obtained might be exploited for the design of the Helium-Cooled Lithium Led (HCLL) BB PHTS since the two concepts show similar features from the BoP point of view.

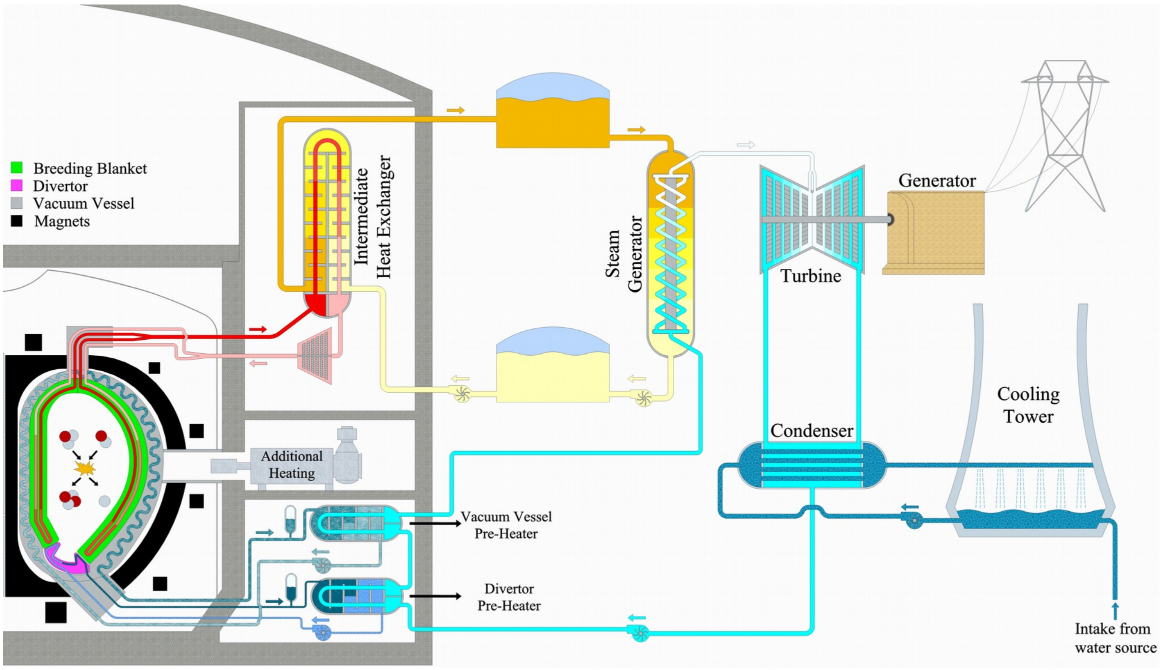

Fig. 1. HCPB "heat transfer chain" conceptual scheme.

2. In-Vessel HCPB BB PHTS design

2.1 Geometrical features

The HCPB BB is designed as a modular concept, where the blanket structure is segmented in smaller modules which help to reduce the thermal stresses. The blanket is subdivided in 18 sectors, each one of 20°. A blanket sector comprises three outboard (OB) and two inboard (IB) segments, leading to a total number of 54 OB and 36 IB segments, respectively. Each OB and IB blanket segment bears seven blanket boxes that are poloidally arranged in row. Each blanket module is fixed to the so-called Back Supporting Structure (BSS) which acts as main structural support for the blanket segments and where the helium collector and distributor units are located [3].

2.2 Cooling scheme

The BSS accommodates two redundant helium loops which feed modules in parallel. Each module is made up of a recurring sub-structure where the coolant coming from the two inlet manifolds enters, cools in series the First Wall (FW) and Breeding zone (BZ) and, finally, goes to the two outlet manifolds [3].

Currently, a "2-side bottom-top" arrangement has been chosen to route the Ex-Vessel piping: the inlet manifolds go inside the VV through the lower ports while the outlet manifolds leave the VV from the upper ports, Fig. 2 [4]. Such cooling scheme has the advantage of ensure a good mass flow distribution through the IB and OB modules, however this choice implies the use of the lower ports which are already crowded due to the presence of Div and VV piping, therefore for Remote Maintenance (RM) and integration reasons it might be necessary, in the future, to route all the BB pipes from the upper ports.

2.3 BB Thermal-hydraulic conditions

The HCBP BB is designed to be cooled by Helium which inlet pressure is 8 MPa [4].

The selected pressure is considered as likely optimum value to achieve: a reduction of circulator power according to $1/p^2$ at constant geometry and a limitation of costs (which increase with p) for pressure vessels, pipes and related engineered safeguards as expansion volumes [5].

The He inlet and outlet temperatures are 300 °C and 500 °C, respectively. Such working window is smaller than the ones usually employed in fission gas reactors, but it is imposed by the lower and upper design limits of the low activation structural steel EUROFER.

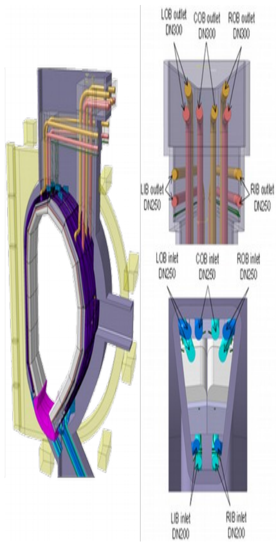

Fig. 2. General and particular views of inlet/outlet manifolds routing through the ports of HCPB sector.

According to the BB pressure and temperature requirements, the study has been focused on two main cases which present two different thermal powers, respectively 2389.1 MW and 2101.7 MW. Both are referred to the new HCPB BB concept [3, 4] and the former has to be intended as "Base case" while the latter is a "Development case" that takes into account the latest progress achieved for this concept.

3. Ex-Vessel HCPB BB PHTS design

3.1 General Criteria

The study of Ex-Vessel HCPB BB PHTS has been mainly focused on the preliminary assessment of the main component sizes and performances in order to identify technical feasibility issues, understand commercial availability and R&D needs, establish layout integration and safety requirements [6, 7]. Therefore, the following design strategies and objectives have been pursued:

- Segmentation and separation of the cooling loops to limit the potential consequences of LOCA events and the size of the main components (piping, heat exchangers, compressors)
- Coolant speed between 40 m/s and 50 m/s as a trade-off choice between the need to limit system pressure drop (hence pumping power) and coolant total inventory through suitable pipe size
- Integration of the PHTS outside of the tokamak bio-shield but as close as possible to be compliant with the high DEMO safety requirements limiting the helium coolant inventory and guaranteeing components and instrumentation qualified life

3.2 System Layout and cooling scheme

According to the abovementioned assumptions a preliminary layout of the HCPB PHTS has been outlined foreseeing a highly degree of segmentation of its cooling loops which are 9. These circuits are completely independent, from mechanical point of view, in order to limit some common mode failures. In particular, there are 3 loops which are designated to cool the IB portion of the tokamak while the other 6 loops are in charge to remove the power from the OB zone. Each IB cooling circuit provides helium to 6 blanket sectors and each OB loop cools the segments of 3 blanket sectors. Fig. 3 shows the 3D-CAD model of HCPB BB PHTS.

The IB loop has 3 main parallel hot legs of which each one collects the helium at 500 °C that comes from 8 hot manifolds exiting from 2 BB sectors and carries it up to the Intermediate Heat eXchanger (IHX). There, the coolant is distributed from the IHX hot portion of the lower plenum through the tube bundle where it can transfer the thermal power to the secondary fluid which is a molten salt. At the IHX outlet the helium has reached about 285°C and 2 pipes route it to 2 redundant compressors which allow helium to circulate along the whole circuit sharing the 50% of the total loop flow. When the coolant leaves compressors at 300°C, it is routed from a cold header to the 3 main parallel cold legs which go down among the tokamak building levels reaching the lower ports floor where they deliver the helium to the cold manifolds of 6 IB sectors.

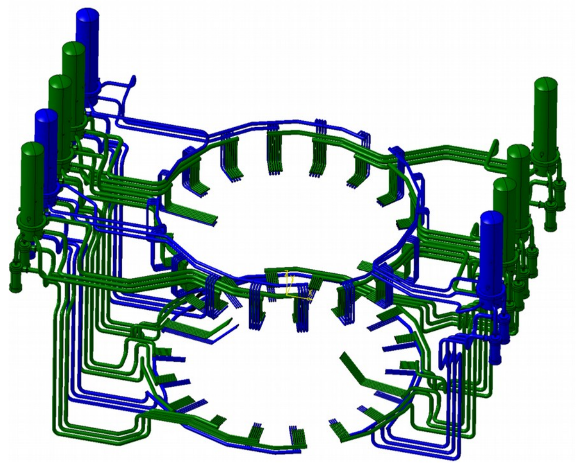

Fig. 3. 3D view of HCPB BB PHTS cooling loops.

The Ex-Vessel OB PHTS cooling scheme is very similar to the IB one but in this case the 3 main hot legs collect helium which comes from 3 sector (6 hot manifolds for each leg) and, as consequence, the main cold legs distribute coolant through the cold manifolds of 3 OB sector.

Table 1 summarises the number of main components per loop.

Table 1. HCPB PHTS main components per loop.

Component	Inboard	Outboard
Hot/Cold manifolds	24/24	18/18
Hot/Cold legs	3/3	3/3
Cold Header	1	1
Compressors	2	2
Heat exchanger	1	1

3.3 Piping

Stainless steel AISI 316L(N) is the material provisionally selected for Ex-Vessel BB PHTS piping since low activation materials are not required outside the VV. Its variant, 316L(N)-IG is indeed the main pressure bearing structural material for ITER [8].

To avoid too much extrapolation respect to the manufacturing technology commonly employed in the PHTS of fission NPPs, it was decided to keep the pipe diameters below DN 800. Such choice, together with the selected maximum helium design velocity and the huge tokamak dimensions [7], implied that:

- the minimum number of hot and cold legs per loop could not be reduced below 3;
- the maximum pipe thickness is 4 cm
- the overall piping length is nearly 9 km
- the total piping volume results to be 1297 m^3

Safety and integration analyses are currently on-going aimed to understand if this option can meet all the prescribed requirements, otherwise manufacturing will have to deal with the use a single hot/cold pipe which diameter should be of about 1.3 meters, as was foreseen in the past designs for a helium-cooled fusion reactor [5]. In fact, the adoption of a bigger pipe would allow a reduction of total piping length to a value of about a third, having a positive impact on integration (less space allocation) and on safety at least for what the mitigation of issues related to the present large number of welding.

Moreover, the use of a pipe with an equivalent total cross-section would decrease the piping distributed pressure drop which, at constant velocity, is proportional to $\sqrt{N}$, where N is the number of parallel pipes.

3.4 Intermediate heat exchanger

A preliminary conceptual thermal-hydraulic design of the IHXs has been performed starting from the basic methods commonly adopted to this purpose. The study has been focused on the “tubes and shell” heat exchanger technology which is the most used in nuclear and conventional industrial applications and, in order to adopt components easily available on the market, tube dimensions have been set in agreement with the TEMA recommendations [9].

In particular, the IHX performances have been numerically investigated in detail by means of in-house developed code based on the Bell-Delaware method as discussed by Taborek in [10].

Moreover, the IHX main parameters (tube diameter, pitch, coolant velocities, etc.) have been chosen among the most promising ones resulting from a previous parametric study [11] and a design solution which could limit pressure drops and bundle tubes as well as the overall dimensions of the heat exchanger has been selected. It has been also decided to let helium circulate through the tube bundle, mainly due to its higher pressure and to the mitigation of LOCA potential effects, placing the molten salt into the shell side.

The tube side Thermal-Hydraulic (T/H) conditions have been chosen to be compliant with the In-Vessel PHTS requirements and a proper set of helium properties have been found in [12]. The shell side boundary conditions have been selected in agreement with [13] and, after a proper literature review of the molten salts technology, it has been decided to use the HITEC salt which properties are provided by one of its major vendor [14].

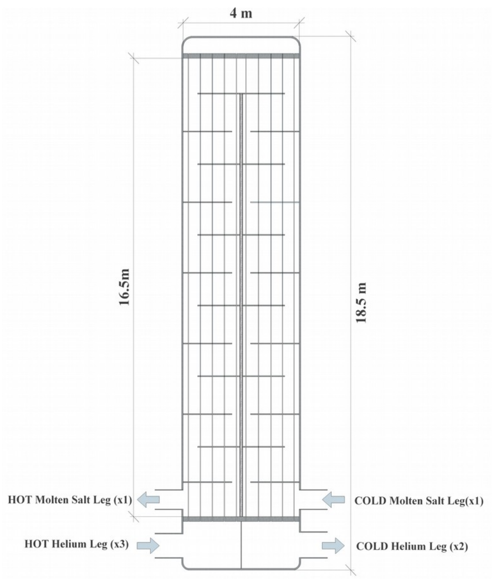

Fig. 4. Conceptual sketch of OB IHX for "Base Case".

Since heat powers extracted from IB and OB are different and they are not in the ratio of one half, the size of the IB/OB IHXs cannot be the same therefore two parallel designs have been carried out.

A two pass shell-side cross-flow configuration (TEMA type F), Fig.4, has been finally considered and encouraging lay-outs have been obtained for both the IB and the OB cooling loops IHXs.

As can be seen from the main data shown in Table 2, the dimensions of the heat exchangers are significant compared to their exchanged power.

This is mainly caused by:

- a not pronounced heat transfer aptitude of the two coolants (relatively low HTCs);
- small temperature differences between helium and molten salt.

Therefore, as further development, the investigation of the potential effects on the IHX design of reducing the intermediate circuit inlet/outlet temperatures will be pursued.

Taking into account the IHXs volumes presented, the total Ex-Vessel + In-Vessel PHTS coolant volume is 2573.1 m^3 ("Base Case") and 2399.8 m^3 ("Development Case")

Table 2. IHXs main data**.**

Parameter	Base Case		Development Case	
	Inboard	Outboard	Inboard	Outboard
Thermal Power [MW]	245.2	304.9	208.6	267.4
T_{in}/T_{out} helium [°C]	500.0/284.5	500.0/285.6	500.0/287.0	500.0/288.1
T_{in}/T_{out} HITEC salt [°C]	268.0/480.0	268.0/480.0	268.0/480.0	268.0/480.0
Tubes active length (per pass) [m]	17.0	16.5	15.7	15.3
Tube number (per pass) [-]	6779	8427	5798	7428
Tube external diameter [mm]	19.05	19.05	19.05	19.05
Helium pressure drop [MPa]	0.12	0.12	0.11	0.11
Total helium volume [m^3]	65.3	79.2	53.0	66.5

3.5 Pressure drop, pumping power

The IB/OB PHTS coolant total pressure drops have been preliminary assessed starting from the previously calculated T/H performances of each PHTS component and, as consequence, also the pumping powers have been calculated. The process has required an iterative procedure because T/H performances of the components, in particular IHXs, depend on the total ΔP and viceversa.

Due to system layout and geometrical features the IB PHTS offers more resistance to the flow respect to the OB PHTS portion both in the "Base case" and in the "Development Case". In fact, in the former case the total pressure drop is 4.57 bar while in the latter it is 3.82 bar. The associated total pumping powers are 53.3 MW and 38.3 MW respectively.

The OB PHTS has a total pressure drop of 4.25 bar in the "Base case" while the estimated head that the compressors must give in the "Development case" is 3.52 bar. Even if OB PHTS shows lower pressure drops compared to the IB circuits, the total pumping powers are higher due to the higher mass flow rates that are circulating inside this portion of the tokamak. They are 123.8 MW and 90.1 MW, respectively for "Base case and "Development case".

Having 6 IB compressors and 12 OB compressors, the powers required by each machinery are about 6.4 MW and 7.5 MW ("Development case"). These values seem to be still high respect to a target of 5 MW which is a power that commonly was achieved in the past in several gas cooled reactors (only isolated cases have higher power) [15] and that is very similar to the one of the compressors employed in the helium fission reactor currently under construction in China [16]. Moving to much from such value may require a specific campaign of R&D for the development of a specific compressor design. In any case, further improvements both in In-Vessel and Ex-Vessel PHTS designs are foreseen with the aim of decreasing the total pressure drop of the reactor and keeping the pumping power under 5 MW per compressors.

4. Conclusion

A preliminary design of the Ex-Vessel PHTS of HCPB BB concept has been developed using the segmentation and separation of the cooling loops as well as the limitation of the coolant pressure drop and of the total coolant inventory as main guidelines to comply not only with functional requirements but also with safety and integration aspects.

A 3+6 IB\OB loops configuration has been obtained characterized by large HXs heat transfer area, piping length and coolant inventory which is judged to be mainly related to the typology (gas) of the coolant considered and its modest differential loop operating temperature.

Further refinements of the design are on-going dealt to optimize IHXs heat transfer area, compressors power and piping length through suitable changes of IHXs secondary operating temperatures, reduction of In-vessel pressure drop and use of pipe having greater diameter.

Acknowledgments

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