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Conceptual design of the enhanced coolant purification systems for the European HCLL and HCPB test blanket modules

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ABSTRACT

The Coolant Purification Systems (CPSs) is one of the most relevant ancillary systems of European Helium Cooled Lead Lithium (HCLL) and Helium Cooled Pebble Bed (HCPB) Test Blanket Modules (TBMs) which are currently in the preliminary design phase in view of their installation and operation in ITER.

The CPS implements mainly two functions: the extraction and concentration of the tritium permeated from the TBM modules into the primary cooling circuit and the chemistry control of helium primary coolant.

During the HCLL and HCPB-TBSs (Test Blanket Systems) Conceptual Design Review (CDR) in 2015 it was recognized the need of reducing the tritium permeation into the Port Cell #16 of ITER. To achieve this and, then, to lower the tritium partial pressure in the Helium Cooling Systems in normal operation, the helium flow-rate treated by each CPS has been increased of almost one order of magnitude.

In 2017, to satisfy the CDR outcomes and the new design requirements requested by Fusion for Energy (F4E, the European Domestic Agency for ITER), ENEA performed a preliminary design of the "enhanced" CPSs.

This paper presents the current design of the "enhanced" CPSs, focusing on design requirements, assumptions, selection of technologies and preliminary components sizing.

1. Introduction

The CPS for both the European TBM concepts [1] has the roles to extract the permeated tritium from the primary cooling circuit, routing it in a suitable form to the downstream tritium processing systems and to keep controlled the coolant chemistry by removing gas impurities and adjusting the oxidation potential of the coolant by proper addition of H_2 and H_2O. Moreover, it has to ensure the implementation of the HCLL and HCPB TBS safety function and to provide confinement to tritiated helium and other radioactive species possibly contained in the process fluid.

The stage processes of the CPS are four: three for the purification of helium (points 1, 2 and 3) and one for the tritium recovery (point 4):

1 Oxidation of Q_2 to Q_2O using a metal oxide;
2 Adsorption of Q_2O and CO_2 by a PTSA (Pressure Temperature Swing Adsorption) columns' system;
3 Adsorption of residual impurities (such as N_2, O_2, CO, CO_2 and CH_4) by a heated getter;
4 Desorption of Q_2O (PTSA in regeneration phase) and reduction to Q_2 by a reducing bed.

One of the main outcomes of the CDR has been the mandatory need to strongly reduce the tritium permeation rate from the TBSs piping into the Port Cell #16, acting on one of the main contributors to the global tritium permeation into this area, the pipes of the HCLL and HCPB Helium Cooling Systems (HCSs). Although, the PbLi loop, in line with the previous analysis, remains the major contributor to the global tritium permeation rate in PC #16. Then, with the objective to lower the tritium partial pressure in the HCSs of around one order of magnitude with respect to the previous design [2,3], the designers have significantly increased the helium flow-rate treated in nominal conditions

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by each CPS, passing from the reference value of 75 Nm^3/h to the actual one of 600 Nm^3/h. The higher helium flow-rate has consequently requested an updated sizing of the CPS components, particularly the oxidizers, the PTSA columns, the reducing beds and the heat exchangers.

2. Design requirements and assumptions

The design guidelines that have generated the additional requirements and consequently the conceptual design of the enhanced CPS [4] are below reported:

- To keep as low as possible the tritium partial pressure in the helium coolant and, then, minimize the tritium permeation rate into the involved Tokamak areas;
- To limit the release of hydrogen to ITER Tritium Plant, while keeping an oxidizing atmosphere in the helium coolant;
- To limit the amount of helium delivered to ITER Tritium Plant;
- To limit the frequency of replacement of the reducing bed in the regeneration loop downstream, with the objective to extend the lifetime of the component to 16 months, then replaced during Long Term Maintenance (LTM).

As agreed with the European Domestic Agency for ITER, these needs have led to the following additional design requirements and assumptions:

- The nominal flow-rate must be in the range 500 ÷ 600 Nm^3/h, being 600 Nm^3/h to be considered as the reference value for the preliminary design for both the HCLL and HCPB TBMs;
- The H_2 partial pressure in HCS and, then, at the CPS inlet must not exceed 300 Pa, to be considered as the reference value for the preliminary design;
- The H_2O partial pressure in HCS and, then, at the CPS inlet must not exceed 10 Pa, to be considered as the reference value for the preliminary design;
- To release to ITER Tritium plant, through Tritium Accountancy System, no more than 30 Nm^3/day of helium per CPS during Plasma Operation State along three shift back-to-back pulses. This means that the PTSA regeneration will have to be accomplished in a closed loop configuration;
- The size of the major CPS components, particularly the reducing bed, shall be such that they can be maintained through the normal provisions foreseen in TCWS vault area, room 11-L4-04 (floor loading limits, cranes, corridors width) [5].

Authors have agreed to perform a unique design for the HCPB and HCLL CPSs operating the two systems with the same conditions.

3. Technologies selection and conceptual design

In this chapter are briefly described the selection of technologies and the conceptual design of the main components of the enhanced CPS [4]. Fig. 1 shows the preliminary 3D layout of the enhanced CPS with the indications of the components described in the following.

The oxidizer provides the conversion of Q_2 to Q_2O and, for some extent of CO to CO_2. The selected solution implies the use of oxidizing particles made of copper oxide working at 250 °C in normal operation. The proposed redundant configuration (two oxidizers in parallel) allows the system to operate continuously when one of the columns is under regeneration. The selected material is an in-situ regenerable copper-based alloy that presents a low and stable pressure drop due to high particle strength in reduced/oxidised state, assuring reliable performances and long predictable lifetime in reduction/oxidation cycles. The sizing has been carried out taking into consideration the oxidation capacity of the selected copper oxide and the superficial velocity provided by the commercial supplier.

PTSA system consists of two adsorbent columns operated in parallel, one working in adsorption at room temperature and high pressure and the other one regenerated at high temperature and lower pressure in the meantime, in a counter-flow configuration. The net effect of the PTSA system is to concentrate in Q_2O the helium sent to reducing beds. For the sizing of this component, the designer has considered a cycle of 48 h of which 24 h for adsorption cycle and 12 h for the stripping of Q_2O during regeneration. A commercial zeolite has been selected as adsorbent bed, able to efficiently remove H_2O/HTO and CO_2. The inner diameter has been fixed considering a superficial velocity high enough to avoid channelling or uneven distribution in the fixed bed, while the column height has been conservatively calculated estimating the necessary length to ensure the complete development of equilibrium zone, mass transfer zone plus an unused bed zone. After a compared study between 1/8 inch and 1/16 inch pebbles, the designers have selected the 1/16 inch pebbles in order to reduce the length of the mass transfer zone resulting in more compact column.

For the purification of the helium feed from the residual impurities, SAES heated getter technology has been confirmed as reference solution. As configuration, only one heated getter has been placed in the Enhanced CPS and it treats continuously a percentage (12.5%) of the whole CPS helium flow-rate. The heated getter, based on a Zr alloy, operated at elevated temperatures, removes impurities by forming irreversible chemical bonds.

After a deep analysis of all possible technological solution for the tritium recovery, the water vapour reduction on metal scavengers, acting as a reducing bed, resulted again as the most mature. In order to guarantee an acceptable lifetime of this components with reasonable dimensions for its handling, the following assumptions have been taken: i) configuration with two reducing beds in parallel; ii) lifetime of each reducing bed 120 full operational days for a total of 240 days for two beds.

The sizing has been performed mainly taking into consideration the reduction capacity of the selected getter material.

Moreover, the buffer tank for recovering helium in depressurization stage of PTSA regeneration and eventual pressure dumping due to compressor present in regeneration circuit has been sized.

All piping, as well as valves are DN25 schedule 80. Furthermore, for all sized components, the designers have chosen as structural material AISI 316 L stainless steel.

Table 1 reports: the total inner volume (including the not actives zones) resulting from the preliminary sizing of key components of enhanced CPS, their structural materials and their operational parameters in Plasma Operation State (POS).

4. CPS design validation

After having carried out the preliminary sizing of the enhanced CPS and implemented the 3D Catia model of the two CPSs in the TCWS vault area, authors started the design validation phase. Both thermo-hydraulic analysis and thermo-mechanical analysis have been performed, taking into account loads and boundary conditions typical of the POS/NOS scenario of ITER. The POS/NOS scenario of ITER is the Normal Operation State scenario under plasma pulses, in which all systems are in nominal conditions of pressure, temperature and mass flow rate. During the pulsed operation of ITER the full plasma power is reached within 30 s and, after 400 s, the power is ramped down within 60 s to decay power. The dwell time between plasma pulses is around 1400 and 1800s.

4.1. Thermo-hydraulic analysis

The preliminary thermo-hydraulic analysis has the scope to determine the CPS total pressure drop and verify that the foreseen HCS circulator head is enough to ensure the helium circulation.

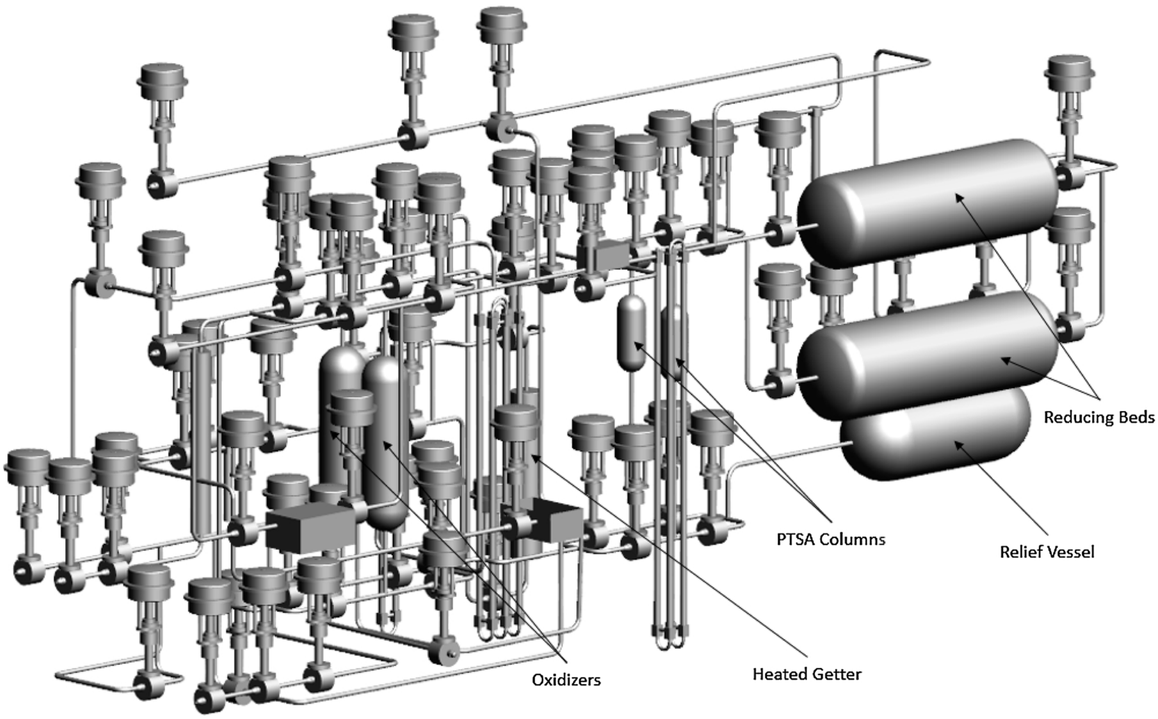

Fig. 1. Enhanced Coolant Purification System 3D cad model.

Authors have considered distributed and concentrated pressure drops of pipelines and components, included pressure drop contribution due to the connection pipes from/to the HCS. Moody formula, a Colebrook equation approximation, has been applied for the determination of the friction coefficient. In fact, this approximation is applicable for Reynolds number in the range of 4000-5 $\times 10^8$ and a relative pipe roughness, ε/D, in the range of 0.0–0.01 as in the enhanced CPS case. In the calculation, a pipe roughness, ε, of 50 μm has been assumed.

The total pressure drops of the system in NOP/POS conditions are very low and only with the almost closed control valve reach the 0.90 MPa.

4.2. Thermo-mechanical analysis

The CPS 3D model has been modelled with ROHR 2 code, reproducing pipelines, vessels, control and isolation valves by means of dedicated components foreseen in the ROHR 2 library.

Thermo-mechanical calculations have been performed considering loads and boundary conditions typical of the POS/NOS scenario. In particular, for loads, authors have applied inertial load, pressure load and thermal load.

The designers have focused the attention on the Von Mises stress and the displacement fields arising within the pipelines and relevant components.

The criteria of the ASME III NC Class 2 design code relevant to the investigated loading scenario have been applied in order to verify that all criteria are fully verified.

Since some critical areas have been detected in the pipeline layout, after the first analysis, authors have introduced some modifications to the piping that allow the system to accommodate intense thermal gradients.

Fig. 2 shows the enhanced CPS loop ASME III NC Class 2 Total stress/σ_{Lim} distribution on the revised layout.

Moreover, for CPS relevant components (PTSA and oxidizer columns) dedicated thermo-mechanical analyses with ANSYS 15 package have been done, verifying that under the operative conditions, the resulting thermo-mechanical stress field is well below the strength limit of the selected structural material. Fig. 3 shows the oxidizer equivalent Von-Mises stress at 250 °C and 8 MPa, (max value in red 56.7 MPa).

5. Conclusion

The conceptual design of the two enhanced Coolant Purification Systems satisfies all the CDR outcomes and the need to reduce

Table 1
Operational parameters, total inner volume and structural materials of CPS key components.

Name	Oxidizer bed	PTSA column	Heated Getter	Reducing Bed
Function	Q_2 oxidation	Q_2O adsorption	Impurity removal	Q_2 recovery
Flow-rate	600 Nm^3/h	600 Nm^3/h in adsorption phase 14 Nm^3/h in desorption phase	75 Nm^3/h	14 Nm^3/h
Pressure	8.0 MPa	8.0 MPa	8.0 MPa	0.3 MPa
Temperature	250 °C	RT in adsorption phase 300 °C in desorption phase	400 °C	400 °C
Capacity of total volume	78.2 l	10.5 l	31.8 l	605.6 l
Functional Material	Copper alloy	Zeolite	SAES getter alloy getter	Zr alloy
Material used as housing/vessel	AISI 316 L	AISI 316 L	AISI 316H / 304H	AISI 316 L

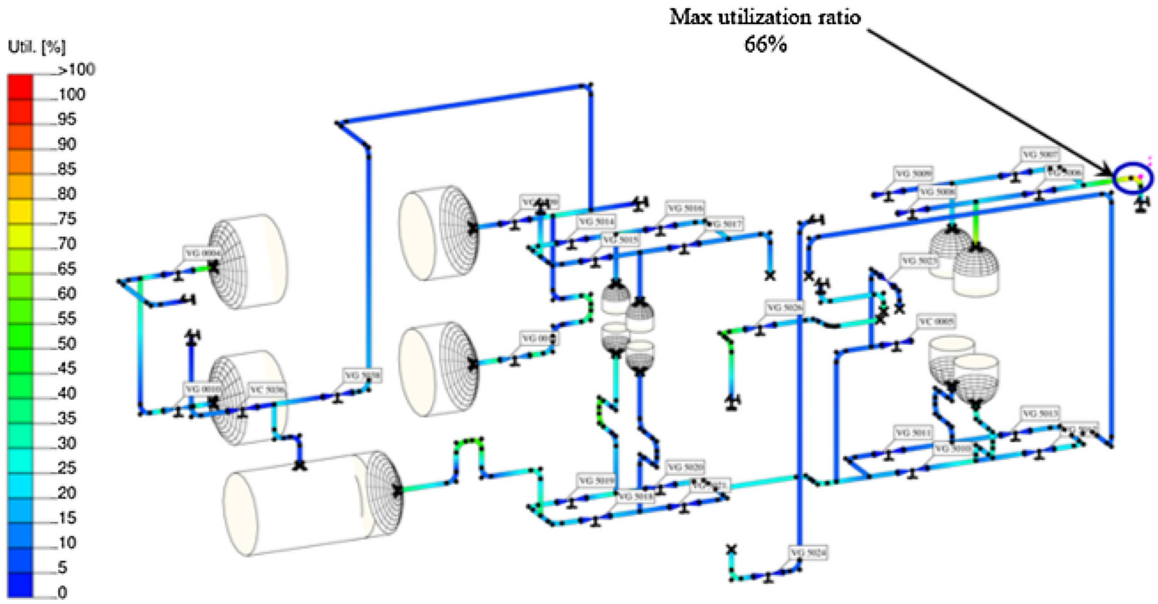

Fig. 2. Enhanced CPS loop ASME III NC Class 2 Total stress/σ_{Lim} distribution (revised layout).

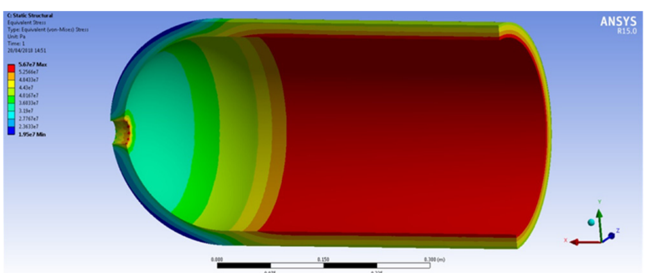

Fig. 3. Oxidizer equivalent Von-Mises stress in POS.

significantly the tritium partial pressure in the HCS. Moreover, the successful results of the analyses carried out on the proposed design makes it suitable for next phases of preliminary and engineering design of the HCLL and HCPB TBMs ancillary systems to be tested in ITER.

Disclaimer

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