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Analysis of the thermal-hydraulic behavior of the EU-DEMO WCLL Breeding Blanket cooling systems during a Loss Of Flow Accident

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The water-cooled EU-DEMO Breeding Blanket (BB) is cooled by two independent circuits, the Breeder Zone (BZ) and the First Wall (FW) Primary Heat Transfer Systems (PHTS). The configuration under study foresees the presence of an Intermediate Heat Transfer System and an Energy Storage System to operate the turbine during both the pulse (2 hours) and the dwell time (10 minutes) at almost constant load, despite the plasma power pulsation. Within the framework of the EUROfusion WPBOP research activity, a RELAP5/Mod3.3 model was developed to investigate the thermal-hydraulic behavior of the primary cooling systems during transient conditions belonging to the category of “Decrease in Coolant System Flow Rate”. The nodalization includes the BB, the PHTS circuits, the BZ Once Through Steam Generators and the FW Heat EXchangers. The model was initially used to simulate the nominal conditions with the pulse and dwell phases. Then, starting from the pulse, a Loss of Flow Accident (LOFA) was selected to preliminary evaluate the PHTS behavior with the aim of the design improvement. LOFA analyses were performed considering the complete loss of both the FW and BZ PHTS main coolant pumps (MCPs). A sensitivity was carried out to assess the impact of the MCPs flywheel on the main PHTS parameters. Transient results highlighted the appropriateness of the current design with no need for further mitigation actions.

Keywords: DEMO, Primary Heat Transfer System, Balance of Plant, RELAP5, Loss of Flow Accident

1. Introduction

The two breeding blanket (BB) concepts selected for the R&D strategy related to the European DEMO reactor are: Water-Cooled Lithium-Lead (WCLL) and Helium-Cooled Pebble Bed (HCPB), [1]. The main function of the BB Primary Heat Transfer Systems (PHTS) is to provide primary coolant at the required thermodynamic conditions to the principal blanket subsystems, First Wall (FW) and Breeder Zone (BZ)., [2][3]. The thermal power removed is then delivered to the Power Conversion System (PCS) to be converted into electricity, [4].

Evaluating the BB PHTS performances in anticipated transient and accident conditions is a key issue for the design of these cooling systems. Such analyses can be performed by using best estimate system codes. Several accidental scenarios referring to DEMO WCLL PHTS, [5][6], have already been investigated with MELCOR code, [7], with the aim of calculating the radiological source term. Instead, RELAP5-3D code, [8], has been used for thermal-hydraulic transient simulations involving the DEMO HCPB PHTS, [9]. For what concerns the operational states, transient analyses have also been carried out with RELAP5/Mod3.3 code in the framework of the R&D activities related to the Water-Cooled Ceramic Breeder (WCCB) blanket concept of the China Fusion Engineering Test Reactor (CFETR), [10].

The calculations presented in this paper are related to DEMO WCLL PHTS. They were carried out within the framework of the EUROfusion Work Package Balance Of Plant (WPBOP). Simulations were performed with a modified version of RELAP5/Mod3.3 code, [8]. This new version was extended by implementing new features relevant for the simulation of fusion reactors, such as new fluids (lithium-lead, HITEC), new heat transfer correlations, etc., [11]. The transient conditions selected belong to the category of “Decrease in Coolant System Flow Rate”. A Loss Of Flow Accident (LOFA) scenario was studied to assess the thermal-hydraulic (TH) response of the primary cooling circuits. In addition, a sensitivity was performed on the flywheel to be added to the PHTS Main Coolant Pumps (MCPs) in order to keep the system temperatures at acceptable values.

2. DEMO WCLL system configuration

DEMO Power Plant is characterized by a pulsed operating regime, based on nine pulses per each day with a burn time of two hours (power pulse) and a dwell time of 10 minutes. The reference parameters and baseline are those of DEMO 2017 concept, [2][3][4]. The reactor CAD model is shown in Fig. 1.

The DEMO blanket design considered is the WCLL BB 2018 V0.6, [2], based on the Single Module Segment (SMS) approach. Water at typical Pressurized Water Reactor (PWR) thermodynamic conditions (295-328 °C and 15.5 MPa) is used as coolant. The blanket relies on liquid lithium-lead as breeder, neutron multiplier and tritium carrier and on EUROFER as structural material. An armour, consisting of a thin tungsten layer is assumed to cover the FW component.

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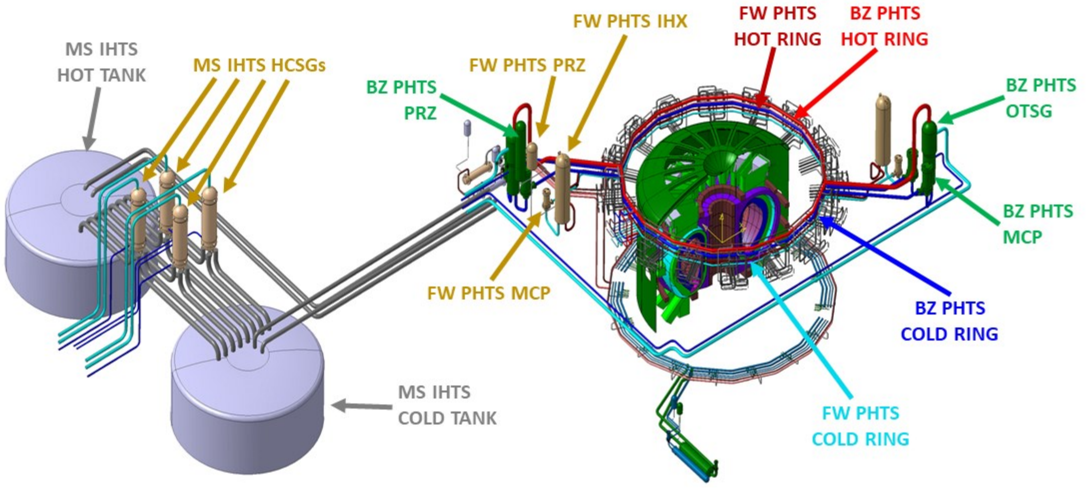

Fig. 1. DEMO WCLL system configuration, [2][3][4].

The overall blanket is divided in 16 sectors (22.5°) in the toroidal direction. Each sector consists of three poloidal segments in the Out Board (OB) blanket and two poloidal segments in the In Board (IB) blanket. The single segment is constituted of about 100 breeding cells (BC) distributed along the poloidal direction. The BC geometry differs along each segment, according to the poloidal position, and between IB and OB segments. The reference BC adopted for modelling purposes is the WCLL 2018 V0.6 Central OB (COB) equatorial cell, described in detail in [12],[13].

The BB is cooled by two independent systems: the BZ PHTS and the FW PHTS, [3][4]. The former delivers thermal power directly to the PCS, by means of two Once Through Steam Generators (OTSG).

Instead, the latter is connected to the Intermediate Heat Transfer System (IHTS) and Energy Storage System (ESS), thanks to two water/molten salt Heat EXchangers (HEX). The ESS consists of two tanks filled with molten salt (HITEC, [14]) at different temperatures. During the plasma pulse, the ESS accumulates a fraction of the FW thermal power, storing molten salt in the hot tank. Then, during the dwell time, this stored energy is transferred to the PCS through four Helicoidal Coil Steam Generators (HCSGs). This configuration allows to keep a continuous and near constant electrical power delivered to the grid in both pulse and dwell phases. The PHTS design foresees two loops for each system, symmetrically disposed along the tokamak circumference (i.e. toroidal direction). The main PHTS components outside the Vacuum Vessel (VV) are:

- The hot and cold rings, distributing and collecting the PHTS mass flow from/to the loops and the tokamak sectors;
- The sector manifolds, divided in collectors (hot) and distributors (cold), connecting the rings to the tokamak sectors;
- The loop piping, connecting the main loop vessel components;
- The BZ OTSGs and the FW HEXs;
- The MCPs, providing the primary coolant flow;
- The pressurizer (PRZ) system, one per PHTS, providing the pressure control function.

A more comprehensive description of the PHTS design is contained in [3],[4] including the main TH parameters and the input power data. For the purposes of the current simulation activity, the PCS section considered is only the BZ OTSGs secondary side. The PCS overall configuration is discussed in [3][4].

3. RELAP5/Mod3.3 nodalization

In order to perform the transient simulations, a complete model of the DEMO WCLL BB PHTS was developed, including all the components inside and outside VV. The features adopted for the RELAP5 input deck are:

- “Slice nodalization” technique was used in the overall model. It consists in realizing the mesh of different system components at the same elevation with control volumes of the same length;
- Actual design elevations were maintained for all the vessel components and piping;
- The node to node ratio, defined as the ratio between the length of two subsequent control volumes (CV), was always kept below 1.25.

3.1 BB Nodalization

The most relevant issues considered while modelling the blanket were: **i)** preserving, as much as possible, the effective BB components design geometry; **ii)** maintaining the design blanket material inventories. In such a way, the component thermal inertia was simulated in the best possible manner, as well as its thermal-hydraulic behavior (i.e. pressure drops, heat transfer, etc.).

The BZ and FW cooling circuits were modelled with two independent hydrodynamic systems, but they are thermally coupled by means of RELAP5 heat structure (HS) components. This approach allows to simulate the heat transfer phenomena which take place inside the BC between FW cooling channels and BZ Double Walled Tubes (DWTs).

For each PHTS, the cooling circuits inside the five poloidal segments (three for OB and two for IB) associated to each DEMO sector were collapsed in three equivalent pipe components, as follows: Left OB (LOB) and Right OB (ROB); Central OB (COB); Left IB (LIB) and Right IB (RIB). The design of the cell located at the equatorial plane of COB, [13], is used as reference for the BCs poloidally distributed along the overall segment. For the others, located in ROB/LOB and LIB/RIB, the aforementioned design is scaled by using the material inventories derived from the CAD model, [2][3].

Each pipe simulates the series of all the components belonging to the BZ or FW cooling circuit inside VV: inlet Feeding Pipe (FP), inlet spinal water manifold, DWTs or FW channels, outlet spinal water manifold and outlet FP. The CV hydraulic properties (flow area, hydraulic diameter, etc.) vary along the pipe length according to the different geometry associated with each component simulated. For the pipes modelling two segments collapsed, the flow area and the water mass flow were doubled, while the length and the hydraulic diameter were kept equal to the design values. The FPs are connected to the PHTS sector collectors and distributors by means of inlet and outlet manifolds. Summarizing, for each PHTS (BZ and FW) and for each sector, the following hydraulic components were used:

- 1 pipe component for the BZ/FW sector distributor;
- 1 branch component for the BZ/FW inlet manifold;
- 1 pipe component to simulate the BZ/FW cooling circuit inside LOB and ROB segments;
- 1 pipe component to simulate the BZ/FW cooling circuit inside the COB segment;
- 1 pipe component to simulate the BZ/FW cooling circuit inside the LIB and the RIB segments;
- 1 branch component for the BZ/FW outlet manifold;
- 1 pipe component for the BZ/FW sector collector.

The RELAP5 HS components were used in the model to simulate: the inventories of the remaining BB materials (W, EUROFER97, LiPb); the power source terms; the heat transfer phenomena which take place inside the BC; the piping thermal insulation (sector collectors and distributors, inlet/outlet FPs).

The LiPb circuit inside the BB was not modelled from a hydrodynamic point of view. Because of its very low velocity inside the blanket, the breeder convective HTC is negligible and the heat transfer is prevalently conductive. Hence, simulating the LiPb as a layer of structural materials in the RELAP5 HS components is an acceptable approximation.

The heat flux incident on the FW, derived from [12],[13], was simulated with a general table and imposed as a boundary condition. The nuclear heating, [12],[13], produced by interactions between neutrons and blanket materials (EUROFER97, W, LiPb, water), was set with an internal power source boundary condition. A schematic view of the BB nodalization is provided by Fig. 4.

3.2 PHTS Nodalization

The PHTS piping, derived from the CAD model, was rigorously simulated in the nodalization, maintaining all the elevations. K-loss coefficients were calculated according to [15] and inserted in junction components to simulate the right pressure drops associated with tees, 90° elbows and abrupt area changes. All the PHTS main components were modelled in detail by using one-dimensional components. The MCPs were simulated with RELAP5 pump components provided with a proportional-integral (PI) controller to set the design mass flow value. The heat transfer inside the BZ OTSGs and the FW HEXs was represented by means of HSs. Sieder-Tate correlation, [16], was used to calculate the molten salt HTC. Temperature Control systems were associated to PCS feedwater and IHTS mass flow at the secondary side of the BZ OTSGs and FW HEXs, respectively. They were implemented to regulate the heat transfer inside these components by tuning the secondary flow. In this way, the required BB inlet temperature is obtained. A full developed pressure control function was implemented for each PHTS, involving a PRZ component equipped with proportional and back-up immersed heaters, spray line, Pilot Operated Relief Valve (PORV) and Safety Relief Valve (SRV). PCS steam lines, constituting the BZ OTSGs secondary side, were modelled and provided with a complete set of steam generator secondary side valves: Turbine Stop Valves (TSVs) and three steps of SRVs (with increasing setpoints). A schematic view of the PHTS nodalization is shown in Fig. 2 and Fig. 3 for BZ and FW, respectively.

4. Simulation activity

The RELAP5 model was initially used to simulate DEMO normal operations. The reference pulsed plasma regime foresees: 2 hours of flat-top at full plasma power, 150 s of power ramp-down, 10 minutes of dwell time and 150 s of power ramp-up, [17]. The plasma ramp-down and ramp-up curves are derived from [17]. The relative trends should be applied to both nuclear heating and incident heat flux. During dwell time only decay heat is left (nearly 1% of the reactor rated power).

In both PHTS, the MCPs are kept running at nominal velocity for the overall simulation (PI controller is disabled). Instead, the temperature and pressure control systems implemented in the input deck are maintained in action. They allow to keep the system in stable operation. During the power pulse, all the design parameters reported in [3][4][11] were obtained as simulation outcomes. During dwell time, the DEMO requirement is to operate the PHTS circuits at nominal flow and average temperature. To match these operational requirements, since the source term is nearly zero, the temperature control systems associated to PCS feedwater and IHTS mass flow decrease these parameters to nearly 1% of their rated value. In this way, the heat transfer inside BZ OTSGs and FW HEXs is enough degraded to avoid PHTS overcooling and keep the primary system temperature at its average value.

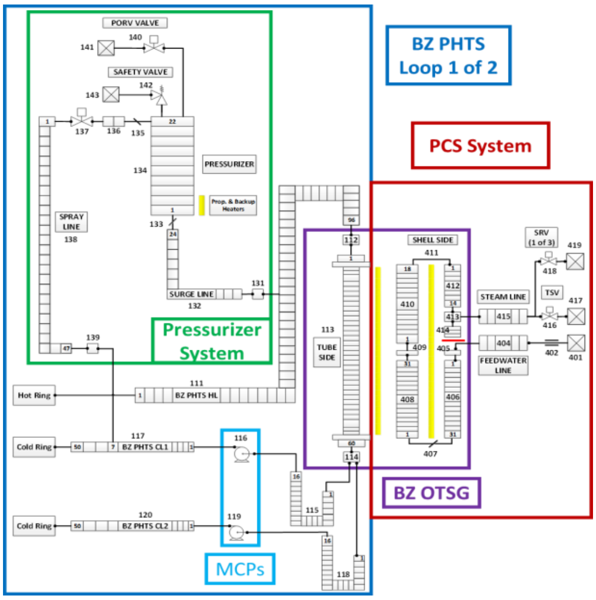

Fig. 2. RELAP5 BZ PHTS nodalization (schematic view).

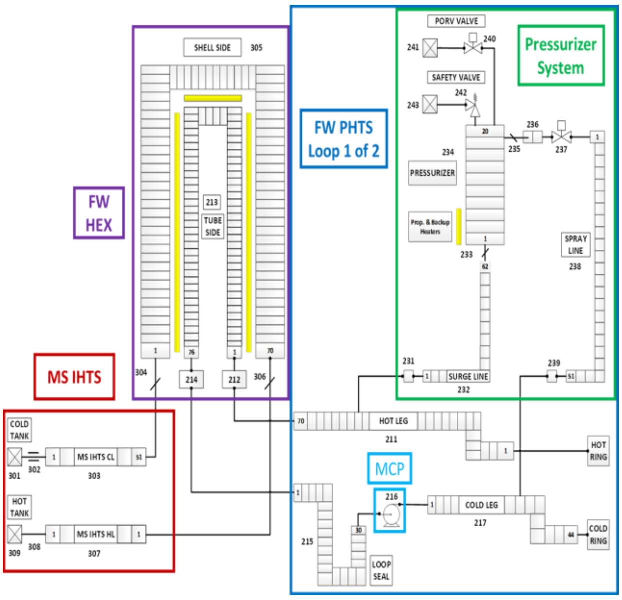

Fig. 3. RELAP5 FW PHTS nodalization (schematic view).

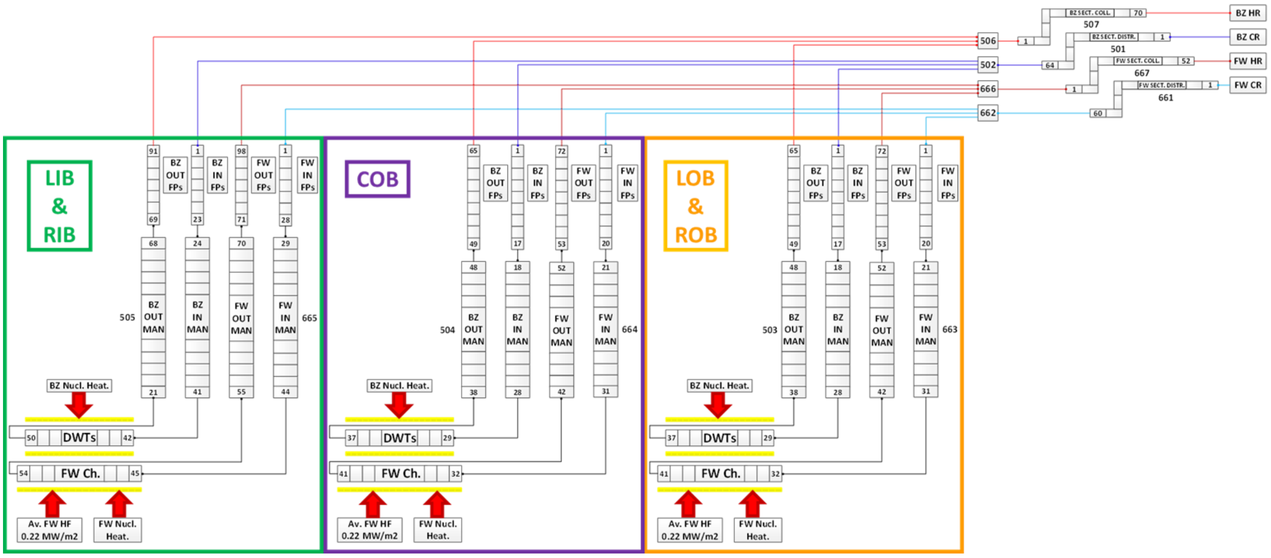

Fig. 4. RELAP5 BB nodalization (schematic view).

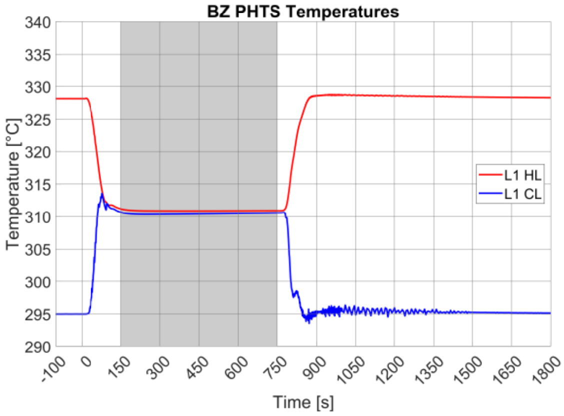

Fig. 5. DEMO normal operations: BZ PHTS loop 1 hot leg (HL) and cold leg (CL) temperatures.

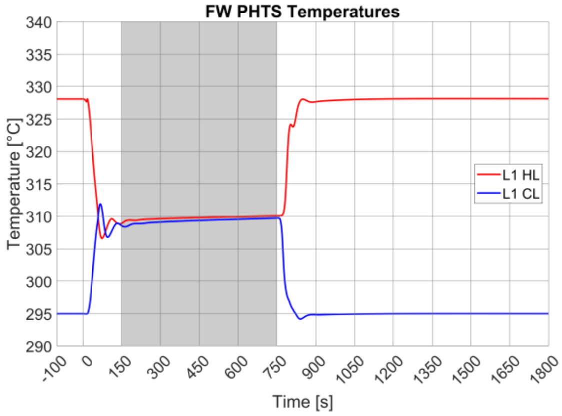

Fig. 6. DEMO normal operations: FW PHTS loop 1 hot leg (HL) and cold leg (CL) temperatures.

Fig. 5 and Fig. 6 show the temperature transients during DEMO normal operations in BZ and FW PHTS (loop 1 of 2), respectively. Dwell time is highlighted with a grey background. Time is reset at the beginning of plasma ramp down. Simulation results reported range from the last 100 s of a pulse phase to the first 15 minutes of the following one. The plasma pulse was conservatively chosen as the initial condition for the accidental transient analysis since it comports higher thermal loads on PHTS cooling systems.

The LOFA Postulated Initiating Event (PIE) is the complete loss of flow in both the BZ and FW PHTS. In the transient simulations, PIE occurs after 20 s of flat top plasma pulse. From Fig. 7 to Fig. 12, the timeline was reset to have PIE at 0 s and the initial steady-state phase was highlighted with a grey background. A time step sensitivity was performed varying this parameter from 1.0E-03 to 1.0E-02. No sensible differences in the simulation results were observed. Time trends reported from Fig. 7 to Fig. 12 are for a time step of 5.0E-03.

A preliminary actuation logic was proposed and implemented for some reactor components. It foresees: **i)** Plasma Termination (PT) is triggered by a low flow signal on MCPs; **ii)** IHTS mass flow ramp-down follows the PT with a delay of 10 s; **iii)** turbine trip (TT) is triggered by a low signal on the OTSGs steam outlet temperature; **iv)** TT is followed by PCS feedwater ramp down and TSVs closure; **v)** PHTS PRZ heaters are cut off on a low-level signal in the PRZ or following the TT; **vi)** PRZ sprays are disabled with the MCPs trip. The plasma ramp-down curve adopted is the same already used in the calculations involving the DEMO normal operations, [17]. With the adoption of this curve, a potential plasma disruption is avoided. The PRZ PORVs/SRVs and the PCS SRVs were supposed to open/close in 0.1 s, while the TSVs in 0.5 s. In this transient simulation, the PI controller related to each BB MCP is disabled. For the primary pumps, the rotational velocity at flat top plasma pulse is imposed as a constant boundary condition until the PIE occurs (first 20 seconds of the simulation). Later, the component coast-down is ruled by the torque-inertia equation. The temperature control systems related to PCS feedwater and IHTS mass flow are also removed. At the transient beginning, these secondary flows are imposed as constant boundary conditions adopting the values obtained for them at flat top plasma pulse. Once triggered by the correspondent signal, the secondary pumps coast down was very preliminary simulated with a linear trend that goes from the nominal value to zero in 10 s.

A sensitivity was carried out to assess the impact on the main PHTS parameters of adding a flywheel to the BZ and FW MCPs. The pump moment of inertia values selected to perform the calculations are reported in Table 1. For what concerns case 1, only motor and impeller contributions were considered and the value indicated in Table 1 was calculated by using formulas in [18]. From case 2 to case 5, an increasing flywheel was added.

Table 1 Selected values for MCP moment of inertia (flywheel sensitivity).

System	Unit	Case 1	Case 2	Case 3	Case 4	Case 5
BZ	kg·m^2	558	1000	2000	3000	4000
FW	kg·m^2	222	524	1048	1573	2097

After PIE, PHTS primary flows start to decrease. The focus on the MCP coastdown is reported in Fig. 7 and Fig. 8, for BZ and FW systems, respectively. The addition of an increasing flywheel slows down the mass flow drop in the PHTS circuits. This effect is sensible in the first 100 s of transient when the forced circulation is prevalent. Later, only natural circulation is left, and the mass flow trend is the same for all the calculations.

The delay in the mass flow decrease retards also the PT triggering (actuated by a low flow signal), as reported in Table 2. This impacts on the BZ and FW temperature peaks at BB outlet, shown in Fig. 9 and Fig. 10. These spikes, occurring at transient beginning, are due to the relation between the ramp down curves belonging to plasma power and primary flow. Even though PT is very close to the MCP trip, plasma heating decreases slower than the MCP flow and the BB outlet temperatures increase. The flywheel addition produces the peak smoothing, avoiding excessive temperatures inside the BB component. Peak temperatures for different cases are collected in Table 2.

After 10 s from PT, IHTS mass flow decreases and the FW HEXs lose their cooling function. Without the power source and the heat sink, the FW system tends to the average temperature (Fig. 10). Increasing the MCP flywheel speeds up this temperature transient, even producing a temporary temperature inversion for the highest value of the parameter (case 5 in Fig. 10). In fact, according to FW PHTS thermal balance, at reduced power (HEXs nearly disabled), higher mass flow rates (i.e. increasing flywheel) correspond to lower temperature differences between hot and cold branches.

The time when TT occurs is shown in Table 2 for each transient simulation. In the time interval between PIE and TT, BZ OTSGs are able to remove power from the primary circuit. Even after the TT, a residual cooling capability is periodically offered by the steam generators in correspondence with the steam line SRVs openings. As a consequence of this lasting cooling function, the BB inlet (i.e. OTSG outlet) temperature initially decreases and only in the mid-term tends to the average one (Fig. 9). The flywheel addition smooths the temperature drop and accelerates the reaching of the average system temperature, as for the FW PHTS. For the BZ system, a temporary temperature inversion is experienced for all the flywheel values. In the long term, this phenomenon disappears for both FW and BZ systems.

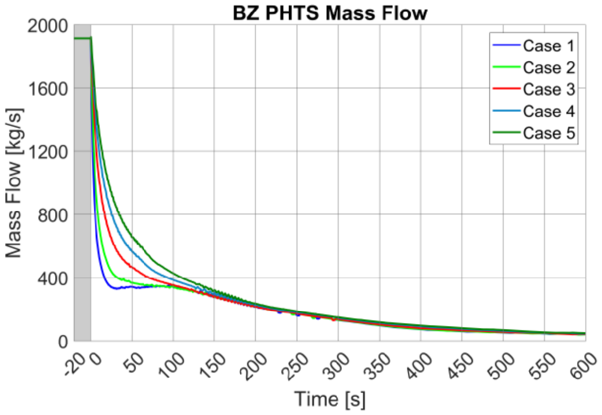

Fig. 7. LOFA transient: BZ MCP mass flow (flywheel sensitivity).

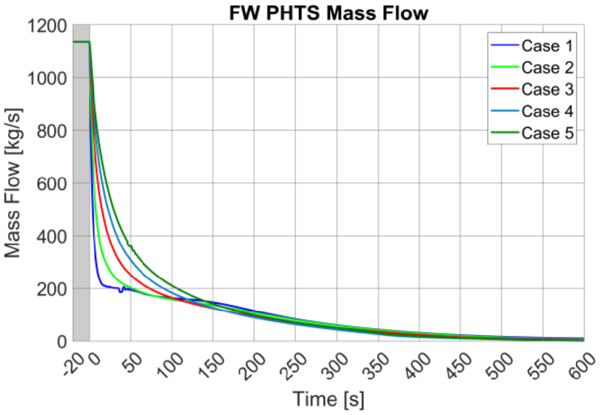

Fig. 8. LOFA transient: FW MCP mass flow (flywheel sensitivity).

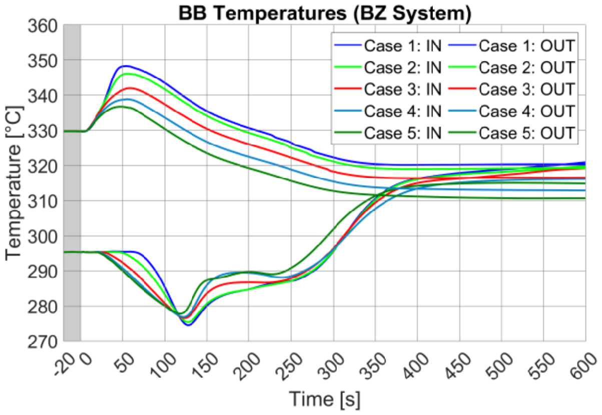

Fig. 9. LOFA transient: BZ system BB In&Out Temperatures (flywheel sensitivity).

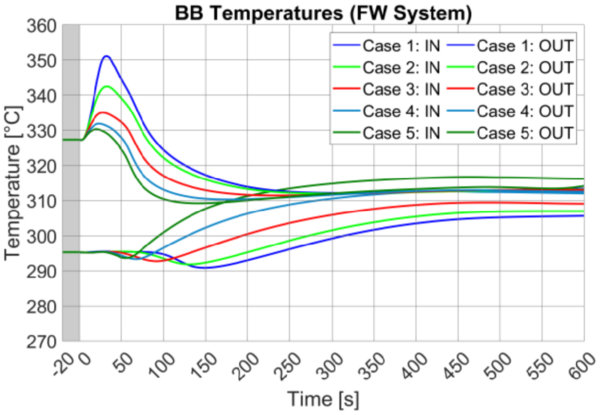

Fig. 10 LOFA transient: FW system BB In&Out Temperatures (flywheel sensitivity)

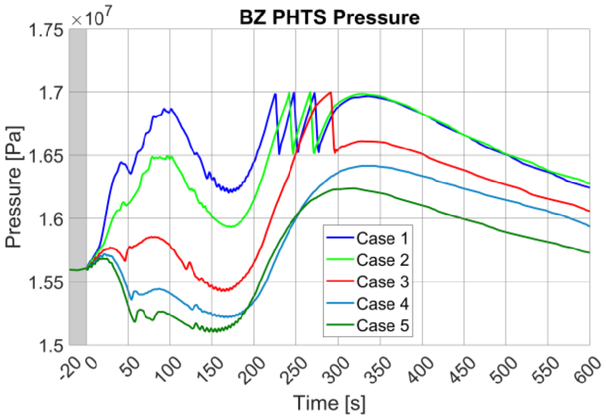

Fig. 11. LOFA transient: BZ PRZ pressure (flywheel sensitivity).

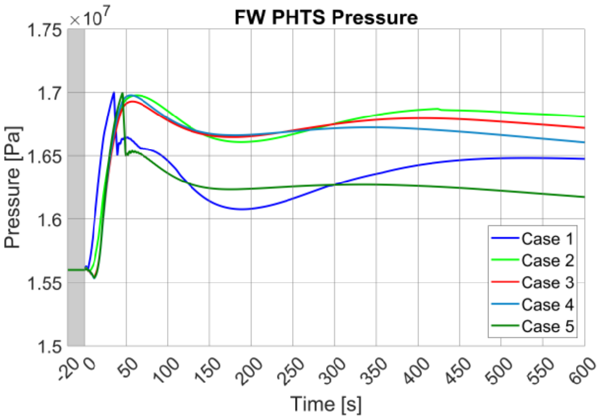

Fig. 12. LOFA transient: FW PRZ pressure (flywheel sensitivity).

Finally, Fig. 11 and Fig. 12 report the BB PHTS pressure trends. The flywheel influence on this parameter is notable. In BZ PHTS, Fig. 11, starting from case 4, its addiction avoids the PRZ PORV opening. Conversely, in the FW system, Fig. 12, the PORV opening occurs in case of absence of MCP flywheel (case 1) and for its maximum value (case 5). The timing of the first PORV opening in both systems, if any, is reported in Table 2 for the different cases. Considering all the BZ and FW PHTS parameters, **case 4** was selected as the best case.

Table 2 Summary Table for LOFA transient (flywheel sensitivity).

#	Unit	System	Case 1	Case 2	Case 3	Case 4 (Best)	Case 5
Plasma Termination (PT)	s	-	0.5	0.5	1	**1.5**	2.5
Turbine Trip	s	-	35.5	38.5	45	**52**	56
Peak temperature	°C	BZ	348	346	342	**339**	337
		FW	351	342	335	**332**	330
First PORV Opening	s	BZ	225	242	291	**-**	-
		FW	35.5	-	-	**-**	45.5

5. Conclusions

The activity is aimed at preliminary evaluating the WCLL BB PHTS performances during anticipated transients and accidental conditions. For the calculations, a modified version of the best-estimate system code RELAP5/Mod3.3 was used. It was developed to enhance the code capabilities with respect to the new issues arising from fusion reactors design process (new HTC correlations, new fluids, etc.). A complete model of the WCLL BB primary cooling systems was prepared. It was initially adopted to simulate the DEMO normal operation (pulse and dwell phases). Pulse was then chosen as the initial condition for transient analysis. A LOFA scenario was selected as reference accidental conditions. The PIE consists in the complete loss of flow in both systems (BZ and FW). A preliminary actuation logic was proposed and implemented for some reactor components. A sensitivity regarding the MCP flywheel was carried out and the different cases were evaluated on the basis of the main PHTS parameters (mass flow, BB inlet and outlet temperatures, PRZ pressure). On the basis of the simulation outcomes, a reference scenario (**case 4**) was selected as the best one. In this scenario, the addition of the flywheel allows to avoid excessive temperatures in the BB component as well as the PRZ PORV opening in both systems. The PHTS design demonstrates its capability in overwhelming such accidental conditions with no need for further mitigation actions. However, the appropriateness of the BB MCPs flywheel selected following the current LOFA analysis must be checked performing transient simulations involving other accidental scenarios, for example the Loss of Coolant Accident.

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