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Thermal-hydraulic modeling and analysis of the Water Cooling System for the ITER Test Blanket Module

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The Water Cooled Lithium Lead (WCLL) is one of the selected breeding blanket (BB) concepts to be investigated in the EUROfusion Breeding Blanket Project (WPBB), and it was also recently chosen as one of the mock-up for ITER Test Blanket Module (TBM) program. The program foresees the test of different BB mock-ups, called Test Blanket Modules, with all the related ancillary systems. A pre-conceptual design of the Water Cooling System (WCS) of the ITER WCLL-TBM was developed considering the same cooling function of the EU-DEMO WCLL-BB primary heat transfer system (PHTS), but matching different boundary conditions: a scaled source power and far lower heat sink temperatures. A complete thermal-hydraulic (TH) model of the WCS loop and TBM set was developed using a modified version of RELAP5/Mod3.3 system code to verify component sizing and to investigate the system behavior during steady-state and transient conditions. The full plasma power scenario was simulated and used as an initial condition for transient calculations. ITER Normal Operational State (NOS) was studied to evaluate the system response. Simulation results highlighted the need for an electric heater to keep the WCS system in stable operation. A sensitivity analysis was carried out to optimize the heater duty cycle.

Keywords: ITER, WCLL, TBM, WCS, RELAP5, NOS

1. Introduction

Demonstrating the feasibility of power extraction from the breeding blanket under DEMO relevant conditions is one of the most important objectives of the TBM testing programme in ITER [1,2,3]. The main function of the EU DEMO WCLL-BB PHTS [4,5] is to provide cooling water to the first wall (FW) and breeding zone (BZ) systems. The PHTS water temperatures and pressure are 568-601 K and 15.5 MPa, respectively. The BB thermal power is then delivered to the Power Conversion System (PCS) to be converted into electricity [6]. The PCS TH boundary conditions are 511-572 K and 6.41 MPa. Similarly, ITER WCLL-TBM WCS removes heat from the TBM set and transfer it to the CCWS. Thanks to the reduced TBM thermal power, a single circuit can be used to provide the cooling function to both the FW and BZ. The heat sink boundary conditions (304-314 K and 1 MPa) are far lower than the TBM ones. A single heat exchanger with these thermal constraints is very difficult to design. Hence, the installation of an economizer at the center of WCS loop is required to divide the overall temperature difference between TBM module and CCWS system in two heat exchangers. The former acts as economizer and the latter as heat sink. The resulting WCS loop has an “eight” shape.

The activity discussed in this paper is articulated in two phases. Firstly, all the main components of the WCS cooling circuit were sized. The resulting system design is described in detail in section 2.

Then, a full thermal-hydraulic model of the WCS loop and TBM set was developed with a modified version of RELAP5/Mod3.3 system code [6,7]. The aim is to validate the component design and to evaluate the system TH performances under steady-state and transient scenarios. Full plasma power state was simulated and then used as initial condition for the transient simulation of the NOS operating regime. The version of RELAP5/Mod3.3 code used for the simulation activity has been extended by implementing the lithium-lead fluid proprieties, as well as some relevant heat transfer correlations for liquid metals [7].

2. WCS configuration

A pulsed plasma regime is foreseen in ITER NOS operating state. The full plasma power is reached in 60 s and, after 450 s of flat-top, the power is ramped down in 200 s. The dwell time between two consecutive plasma pulses is 1090 s [8]. During the flat-top, the TBM set overall heating consists of 743 kW_{th} and the TH boundary conditions required to the cooling water are 568-601 K and 15.5 MPa, as in DEMO WCLL-BB PHTS [7]. The total water mass flow necessary to cool down both the BZ and FW systems is 3.85 kg/s.

The WCLL-TBM and its ancillary systems are located in the ITER Tokamak building, in the space once reserved to the HCLL-TBM. The WCS loop is mainly installed in TWCS area (room 11-L4-04) on building level four, with some components, included the TBM, placed in Port Cell C16, on level one. A vertical shaft

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connects the two locations [9]. A scheme of the WCS system configuration in room 11-L4-04 is shown in Fig. 1, [10]. As stated in the introduction, the WCS loop has an eight shape, with the TBM installed on the high temperature side and the pumping system located in the low temperature branch.

A Hairpin heat exchanger (HX-0001) is placed at the center of the loop with the function of heat economizer. Its sizing criteria are: provide cooling water to the TBM with the required inlet thermodynamic conditions; limit the average temperature difference between WCS and CCWS systems in the heat sink (HX-0002) below 100 K. This parameter strongly influences the size and technical feasibility of the heat sink. The hot water outcoming the TBM at 601 K, is cooled in the HX-0001 down to 430 K. At the same time, the cold water coming from the WCS pumping system is heated up from 384 K to 568 K, required at TBM inlet. The HX-0001 rated power is 3.2 MW_{th}.

The heat sink (HX-0002) is a Shell & Tubes heat exchanger located before the pumping system and the connections with the Coolant Purification System (CPS). Its sizing power is the TBM rated power. In this component, WCS water is furtherly cooled down from 430 K to 384 K. The TH conditions of CCWS water are sizing constraints for the heat exchanger design, 304-314 K and 1 MPa. The required CCWS mass flow is 17.8 kg/s.

To increase the reliability and availability of the loop, the current design foresees two identical centrifugal water pumps in parallel. During NOS only one of the two pumps is on, the other is for backup. Both circulators are designed to provide the rated mass flow independently for cooling the TBM. The total power installed is about 5 kW.

An electric heater (HT-0001) is installed in the WCS system downstream the HX-0001. It supplies the deficiency of TBM thermal power. In NOS operating state, since a pulsed plasma regime is foreseen, this happens during the dwell time between two consecutive plasma pulses. The HT-0001 sizing power is equal to the TBM rated power. The heater is a key component to keep the WCS loop in stable operation during the entire NOS. Its function is more widely discussed in section 4.2.

The pressurizer is connected to the hot leg and guarantees the pressure control function. It maintains the water pressure at TBM inlet at the required value, compensating the coolant temperature variations due to the pulsed plasma regime and, in general, to other transient conditions. In the current design, the needed pressurizer volume is almost 1.5 m^3. The WCS loop, as a system operating at high pressure, must be equipped with protection devices against low and over-pressure transients. Hence, the pressurizer is provided with electric heaters and a spray line connected to the cold leg. These systems are installed to face respectively under and overpressure transients, occurring during normal operating conditions, and to limit pressure changes during transient conditions. In case of abnormal overpressure transients, if spray nozzles fail in reducing pressure, at the top of pressurizer is also foreseen the presence of a PORV valve and a Safety valve. They are both related to a relief line that connects the pressurizer to a Pressure Relief Tank (PRT), allowing the discharge of steam. The PORV valve is provided with a lower set-point than the safety valve to limit the number of challenges of this latter component.

3. RELAP5/Mod3.3 nodalization

In order to perform steady-state and transient simulations of the ITER WCLL TBM system (TBS), a computational model of the TBM set and WCS loop was developed. Their TH nodalizations are discussed separately in subsections 3.1 and 3.2, respectively. The features adopted for the RELAP5/Mod3.3 input deck are:

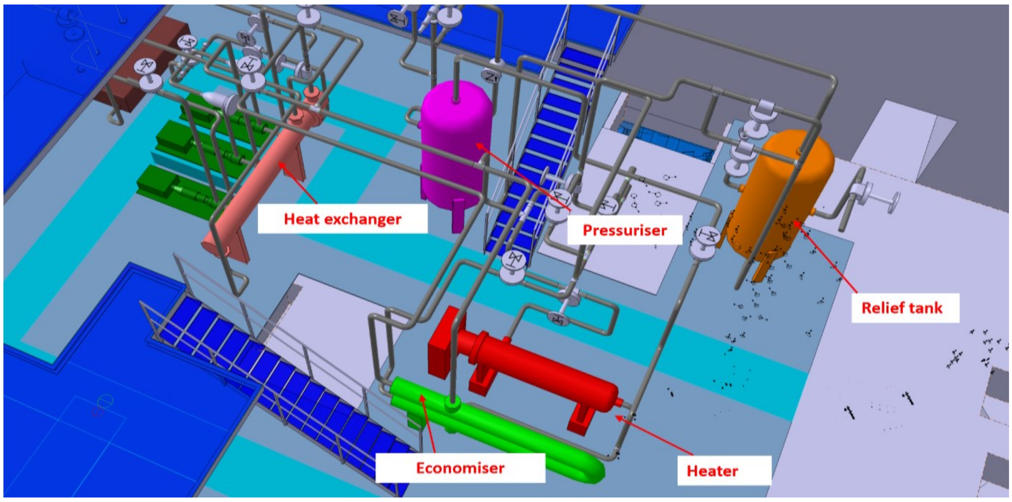

Fig. 1. WCS system configuration in room 11-L4-04, [9].

- "Slice nodalization" technique is applied, consisting in realizing the mesh volumes of different components at the same elevation with the same cell length;
- Actual design elevations are maintained for any component of the system;
- The node to node ratio, defined as the ratio between the length of two subsequent mesh volumes, is kept below 1.25.

3.1 TBM Set TH Nodalization

The TBM design used as reference for the model development is derived from CAD contained in [11]. At TBM inlet, the primary water is split in two main flow paths, the former cooling the FW and the latter removing power from the BZ and the lateral Side Caps (SC). Both flow paths are provided with a vertical inlet manifold. Instead, there is a single outlet manifold to homogenize the TBM outlet water temperature. Each manifold is modelled with a vertical pipe component. The FW design foresees "Vertical" (i.e. radial-poloidal) cooling with one pass 7x7 mm squared channels. They are in counter-current one other two. The 32 channels are modelled with two equivalent pipes (one for each flow verse), to respect the cooling symmetry. The BZ consists of 16 Breeding Units (BUs), where flows the Lithium-Lead (LiPb) liquid breeder, cooled by 60 Double Wall Tubes (DWTs) with internal diameter of 8 mm. For what concerns LiPb, each BUs is modelled with an equivalent pipe. Instead, the DWTs are collapsed in 16 equivalent pipes according to their vertical (poloidal) position. Each lateral SC hosts eight C-shaped 6x6 mm squared channels. Any pair of SC channels at the same vertical (poloidal) elevation is simulated with an equivalent pipe (8 in total). The LiPb manifold is unique but divided by vertical spacers in four subsections, two inlets and two outlets. Each one is modelled with a vertical equivalent pipe component. Any pair of inlet/outlet subsections is connected to a vertical stack of eight BUs, resulting in two parallel flow paths. The total LiPb flow mass is uniformly divided between them. All the internal EUROFER97 components were simulated by means of heat structures. Heat structures are also used to simulate the heat transfer phenomena between water and LiPb and water and steel structures. The FW power source is modelled by means of two terms: an imposed heat flux on the FW front surface (0.3 MW/m^2); a radially decreasing power volumetric density associated to the water in FW channels and the EUROFER97 of FW steel liner. No references were found for the BZ power source so it is all associated to the liquid breeder flowing in the BUs. The TBM model maintains all the geometrical data (hydraulic diameters, flow areas, lengths, elevations, material thickness, heat transfer surfaces) related to fluid flow paths and steel internals, [11]. The fluid and steel inventories are also strictly maintained. An overview of the nodalization of the water and LiPb flow paths inside the TBM set is provided by Fig. 2 and Fig. 3.

3.2 WCS System TH Nodalization

The WCS pipelines routing is derived from CAD model [10] and is rigorously simulated in the nodalization, maintaining all the elevations. K-loss coefficients were calculated according to [12] and inserted in junction component to simulate the right pressure drops associated to Valves, Filters, Tees, 90° elbows and abrupt area changes. All the WCS main components were modelled with one-dimensional components. The tubes of the HX-0001 and HX-0002 were simulated with equivalent pipes. The pipelines of the CCWS system belonging to room 11-L4-04 were also included in the overall nodalization. The heat transfer inside the heat exchangers and the electrical heating associated to the pressurizer and the HT-0001 are represented by means of heat structures. Because of space constraints, Fig. 4 shows only a schematic representation of the WCS system nodalization.

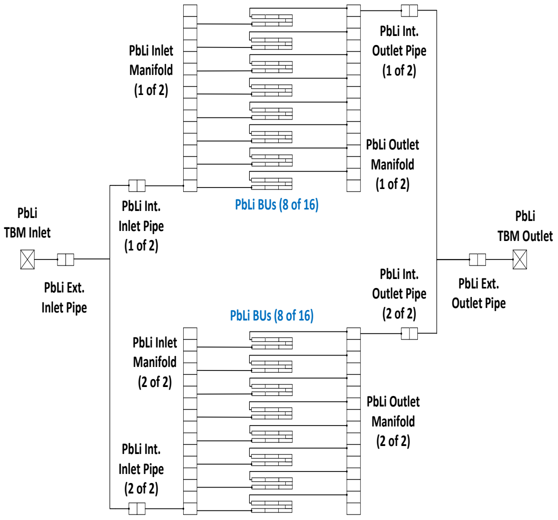

Fig. 2. RELAP5 nodalization of LiPb flow paths inside TBM set.

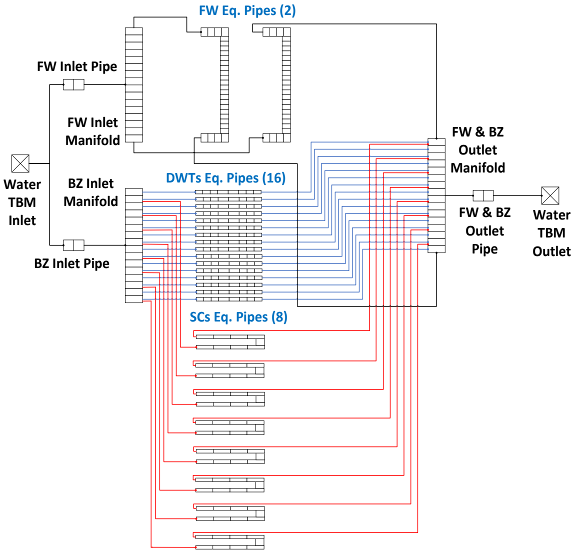

Fig. 3. RELAP5 nodalization of water flow paths inside TBM set.

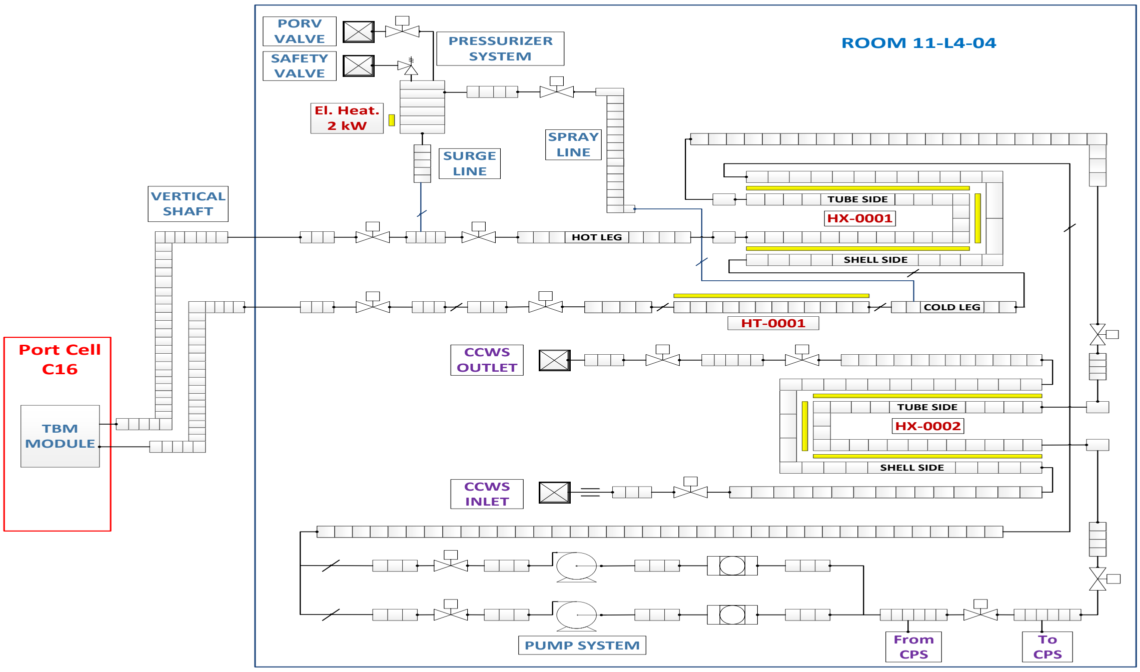

Fig. 4. WCS system overall nodalization.

4. Results

This section contains the main results obtained by using RELAP5/Mod3.3 system code to perform TH simulations. Subsection 4.1 contains the parameters calculated for full plasma power condition, while subsection 4.2 reports the variable time trends during the entire NOS operating regime.

4.1 Full plasma power condition

A steady-state calculation was run to qualify the RELAP5/Mod3.3 TH model described so far. The LiPb TH conditions at TBM inlet and the CCWS water TH conditions at HX-0002 inlet are imposed as boundary conditions by means of RELAP5 time-dependent volume and time-dependent junction components. Instead, WCS system main coolant pump (MCP) is simulated with a RELAP5 pump component. Hence, the WCS system mass flow derives from the balance between available pump head and loop pressure drops. HT-0001 power is set to zero for this simulation. All the main TH parameters of the TBS system were computed and compared with the design values derived from [10]. Tab. 1 summarizes the simulation outcomes. The WCS and CCWS temperatures are well simulated by the code. As expected by design, the LiPb is nearly isothermal between TBM inlet and outlet. The WCS mass flow resulting from the calculation is exactly the design one, so the pump model used is correct. The exchanged power related to HX-0001 is the correct one, so the TH model of the economizer is well set. The HX-0002 power is the sum of the TBM power delivered to the WCS water (underestimated of a 0.5%) and the pumping power (nearly 3 kW).

Table 1. TBS system TH parameters at full plasma power condition.

Parameters	Units	Design Value	Relap5/ Mod3.3 Value
WCS System			
TBM In Temp	K	568	568.6
TBM Out Temp	K	601	601.3
HX-0001 Out Temp	K	430	430.4
HX-0002 Out Temp	K	384	384.8
WCS Mass Flow	kg/s	3.85	3.85
TBM Power to WCS	kW	743	740
HX-0001 Power	kW	3200	3200
HX-0002 Power	kW	743	743
CCWS System			
CCWS Out Temp	K	314	314
LiPb Loop			
TBM Out Temp	K	603	604.4
TBM Power to LiPb	kW	0	0.066

4.2 NOS operating regime

The design and RELAP5 modelling activities discussed in the previous sections are aimed at studying the TBS system behavior during the pulsed regime characterizing the NOS operating state. The plasma power trend adopted for simulation purposes is the one described in Sect. 2. Starting with the flat-top phase, transient calculations are run for 9000 s, corresponding to five complete cycles of the pulsed regime. To investigate a DEMO relevant operational transient, the WCS system MCP is kept running at nominal velocity during all the simulation, maintaining the WCS water mass flow almost constant. Also the LiPb TH conditions at TBM inlet and the CCWS TH conditions at HX-0002 inlet do not vary during the calculation. The temperature at TBM outlet is selected as control parameter to analyze the system TH performances. This quantity is chosen since it is the maximum temperature in WCS system and because, in the operational transient considered, the average loop temperature follows the same time trend of the selected parameter, as shown by the simulation results. Thus, it can be considered representative of the loop thermal behavior. The control parameter is used in Fig. 5 and Fig. 6 to compare the different cases. A first calculation, named case 1, was run setting to zero the HT-0001 power. As shown by Fig. 5, after the initial flat-top, the fluid temperature starts to decrease with a nearly sawtooth trend. During dwell time, represented in Fig. 5 and in the following figures as a grey area, there is no plasma power but the WCS nominal flow is maintained and the heat sink is still in operation. Since the heat sink temperatures are very low, this provokes an excessive cooling of the WCS system. When plasma power is ramped up, the WCS system temperatures increase again, but the pulse phase is too short to allow the fluid to return at the original temperature values. As a result, cycle after cycle, the maximum, and consequently also the average, fluid temperature in WCS loop decreases. The same trend is valid also for the CCWS outlet temperature from HX-0002. This simulation proves the need, during dwell time, of the HT-0001 supply power to avoid the progressive loop cooling.

Since no control logic is available for the HT-0001 component, as a first tentative, the HT-0001 sizing power was assumed equals to the TBM rated power and the heater duty cycle was reverted with respect to the pulsed plasma regime. A second calculation, case 2, was run setting this HT-0001 power figure. Fig. 5 shows that, in this simulation, the average value of the TBM outlet temperature keeps constant during the overall transient, avoiding the loop cooling. Although, there are significantly negative and positive thermal spikes (-10/+15K) which constitute a relevant thermomechanical load for the TBM set and WCS system components.

The TBM outlet temperature fluctuations are caused by the relative timing between the plasma power figure and the HT-0001 power figure. During plasma power ramp down, the water heated by the HT-0001 must flow through the descendant shaft to reach the TBM outlet and it arrives with a time delay. Thus, there is a time window in which temperature drops, provoking the negative spikes. The opposite occurs during plasma power ramp-up. Hot water still heated by HT-0001 reaches the TBM with a delay and is also heated by plasma power that starts to increase. This produces positive spikes. In both cases, the low thermal inertia of the TBM set (due to its small LiPb and steel inventories) does not help in mitigating the thermal fluctuations. The delay due to the allocation of HT-0001 and TBM set at different levels of tokamak building has a strong influence on the thermal fluctuations. This cannot be solved placing the electrical heater in Port Cell C16, since no space is available in this room for the component. The delay could be compensated by anticipating the chosen heater duty cycle. A third simulation, case 3, was performed considering a time anticipation for the HT-0001 power figure of 60 s. This value was chosen considering the time needed to the WCS water to flow from HT-0001 outlet to TBM inlet (nearly 45 m of pipelines with a fluid velocity of approximately 1 m/s) increased to take also into account the system inertia. As reported in Fig. 5, this solution allows to strongly reduce the temperature oscillations (-2/+5 K) at TBM outlet and to obtain a system more stable operation along the overall NOS operating transient.

Then, in order to optimize the design solution adopted, a sensitivity was carried out on the HT-0001 anticipation time. Simulations were run with different values of this parameter, spanning from 40 s to 90 s. The time trends of TBM outlet temperature during the overall simulation length for all the cases considered are collected in Fig. 6A. A focus on the single transition is contained in Fig. 6B and helps to better understand the evolution of the temperature fluctuations with the variation of the sensitivity parameter. When plasma power is ramped up, the magnitude of the positive spike decreases increasing the anticipation time. Although, increasing too much the switch-off of the HT-0001 produces the occurrence of a time window before the switch-on of plasma power when no power sources are present and the WCS temperature drops. The best compromise to reduce the positive spike and to nearly avoid the negative one is to use an anticipation time in the range between 65 and 70 s. The same is valid for the plasma power ramp down. This transition is smoother than the previous one since its time length is more than double (200 s with respect to 60 s). With increasing anticipation time, the temperature drop is reduced. However, an excessive value of the sensitivity parameter leads the WCS temperature to firstly rise and only in a second moment to decrease. The more regular decreasing trend is the one associated to an anticipation time belonging to the range between 65 and 70 s.

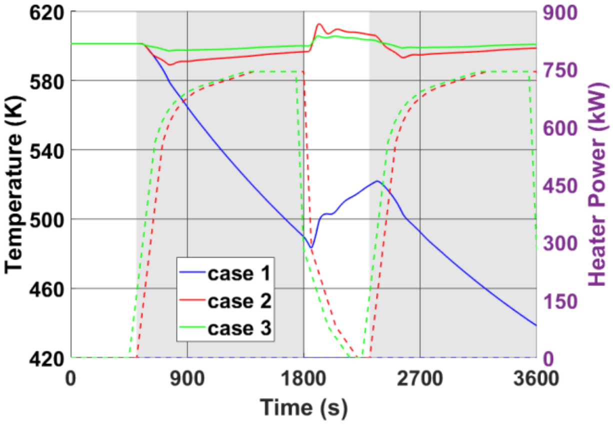

Fig. 5. TBM outlet temperature during NOS in case of: absence of HT-0001 heating (case 1); presence of HT-0001 heating (case 2); presence of HT-0001 heating with power ramps anticipated of 60 s with respect to plasma pulsed regime (case 3).

For the reference case (70 s of time advance) a deeper analysis of the TBS system behavior is discussed in the following. Fig. 7, Fig. 8, Fig. 9 and Fig. 10 collect the time trends related to the main WCS, CCWS and LiPb loop TH parameters. Thanks to the sensitivity performed on the anticipation time, the TBM outlet and HT-0001 inlet temperatures are characterized by low oscillations, the former in the range of 599-605 K and the latter in the range of 567-572 K (Fig. 7). On the contrary, during NOS the TBM inlet temperature varies between the other two temperatures, increasing during dwell and decreasing during pulse (Fig. 7). This means that also the TBM average temperature varies along the transient leading to significant thermal stresses on the TBM set. This aspect must be further investigated to assess if the TBM can undergo such thermomechanical strains. Fig. 8 shows that the fluctuations characterizing the water temperatures in the hot branch of the WCS loop nearly disappear in the cold branch and in the CCWS system. Fig. 9 collects the time trends of the power exchanged with WCS water in the TBM, the HT-0001 and the heat sink. What is significant to highlight is that, thanks to the duty cycle adopted for the heater, the heat sink power keeps almost constant during all the NOS operating state. The LiPb TBM outlet temperature, shown in Fig.10, follows the same oscillations of the WCS water TBM inlet temperature but with reduced amplitude (+/- 3 K) around the mean value that is the LiPb TBM inlet temperature of 603 K. The LiPb power trend is the same of the outlet temperature with negligible oscillation amplitude (+/- 0.15 kW). For the reference case a time step sensitivity was performed varying this parameter from 1E-03 to 1E-02. No sensible differences in the time trends were observed. The time trends reported in Fig.7 to Fig. 10 are for a time trend of 5E-03.

5. Conclusions

The activity discussed in this paper is aimed at developing a TH transient analysis in support to the pre-conceptual design of the ITER WCLL-TBM WCS ancillary system. The design phase consisted in component sizing and then in the sizing verification by means of RELAP5/Mod3.3 system code. Once qualified the loop TH model, the system behavior during the NOS operating state was studied and a solution was found to guarantee a stable operation along the overall transient. An electrical heater HT-0001 was placed in the circuit and its duty cycle was optimized to keep constant the water temperature at TBM outlet. By anticipating the heater power ramps of 70 s with respect to the pulsed plasma regime, the TBM outlet temperature is nearly constant during the entire NOS operating state. Further investigations are needed to verify in detail the TBM operation during the NOS transient and the WCS system behavior during accidental scenarios.

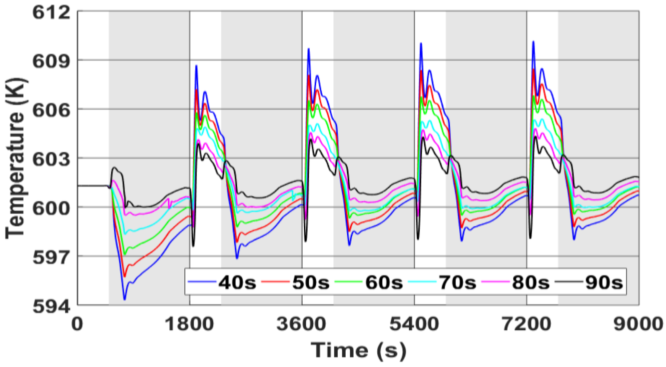

Fig. 6A. TBM outlet temperature during NOS by varying the HT-0001 heating anticipation time.

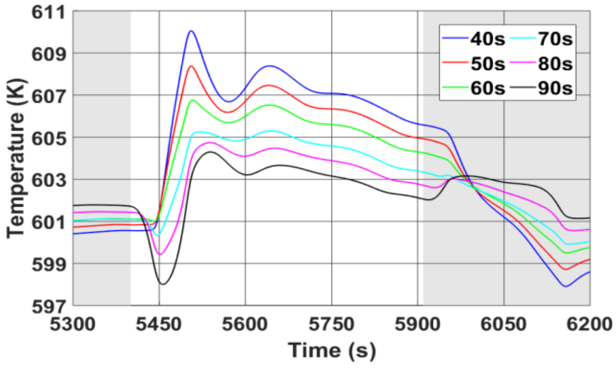

Fig. 6B. TBM outlet temperature during NOS by varying the HT-0001 heating anticipation time (zoom on the single transition).

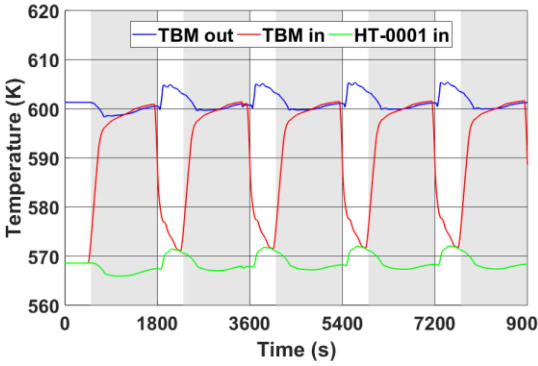

Fig. 7. Water temperatures during NOS in WCS loop hot branch (70 s of time advance).

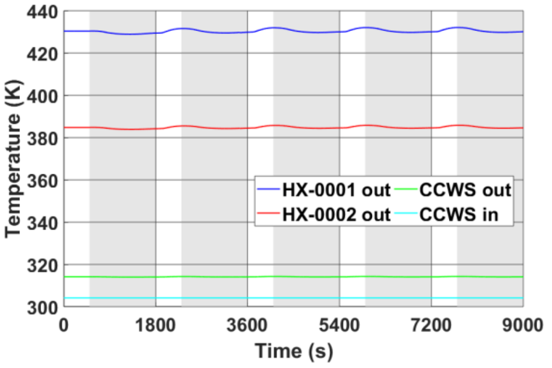

Fig. 8. Water temperatures during NOS in WCS loop cold branch and CCWS system (70 s of time advance).

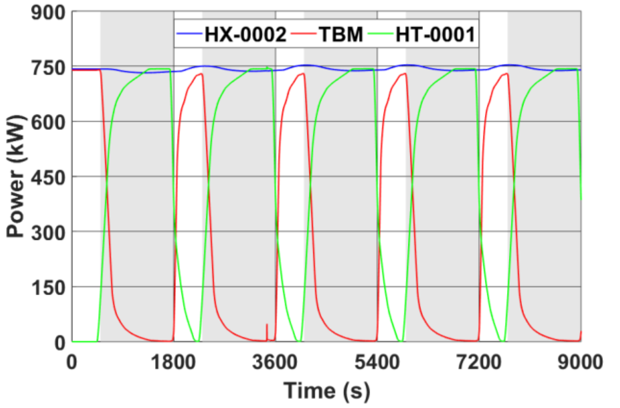

Fig. 9. Power exchanged with WCS water at different locations during NOS (70 s of time advance).

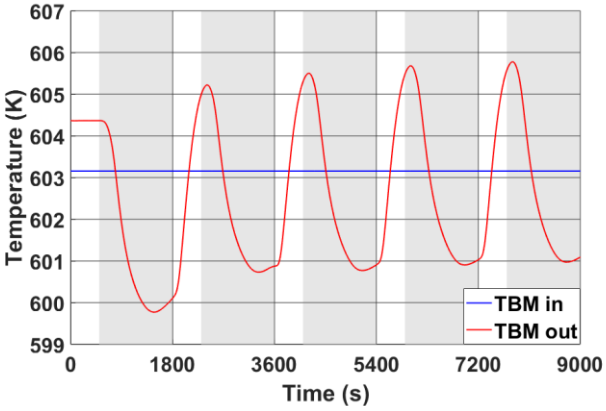

Fig. 10. LiPb TBM inlet and outlet temperatures during NOS (70 s of time advance).

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