Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Evaluation of the thermal-hydraulic performances of a once-through steam generator in nuclear fusion applications

Evaluation of the thermal-hydraulic performances of a once-through steam generator in nuclear fusion applications

Federico Galli, Cristiano Ciurluini*, Vincenzo Narcisi, Fabio Giannetti, Gianfranco Caruso

DIAEE – Nuclear Section, "Sapienza" University of Rome, Corso Vittorio Emanuele II, 244, 00186, Rome, Italy
* Corresponding author e-mail: cristiano.ciurluini@uniroma1.it

Abstract. After decades of operation in nuclear power plants, Once-Through Steam Generators (OTSGs) were recently proposed for nuclear fusion applications. In particular, they are supposed to be installed in the primary cooling systems of the European Union Demonstration fusion power plant (EU-DEMO). One of the key reactor components is the Breeding blanket (BB). Among the BB concepts that are currently under study, Water-Cooled Lithium-Lead (WCLL) option was considered for this work. The WCLL blanket is divided in two main subsystems, the breeder zone (BZ) and the first wall (FW), each one provided with an independent cooling circuit, named Primary Heat Transfer System (PHTS). Thermal power removed from BB by BZ and FW PHTS is driven to the Power Conversion System (PCS) to be converted into electricity. The thermal coupling is ensured by two OTSGs per system. At the Department of Astronautical, Electrical and Energy Engineering (DIAEE) of Sapienza University of Rome, a simulation activity was carried out to understand the component thermal-hydraulic behavior during DEMO normal operations. For calculation purposes, a full model of the steam generator was prepared by using a modified version of RELAP5/MOD3.3 system code. The computational activity performed allows to preliminary characterize the OTSG thermal-hydraulic performances during both pulse and dwell phases.

Keywords: DEMO, Primary Heat Transfer System, Balance of Plant, RELAP5, pulse/dwell transition.

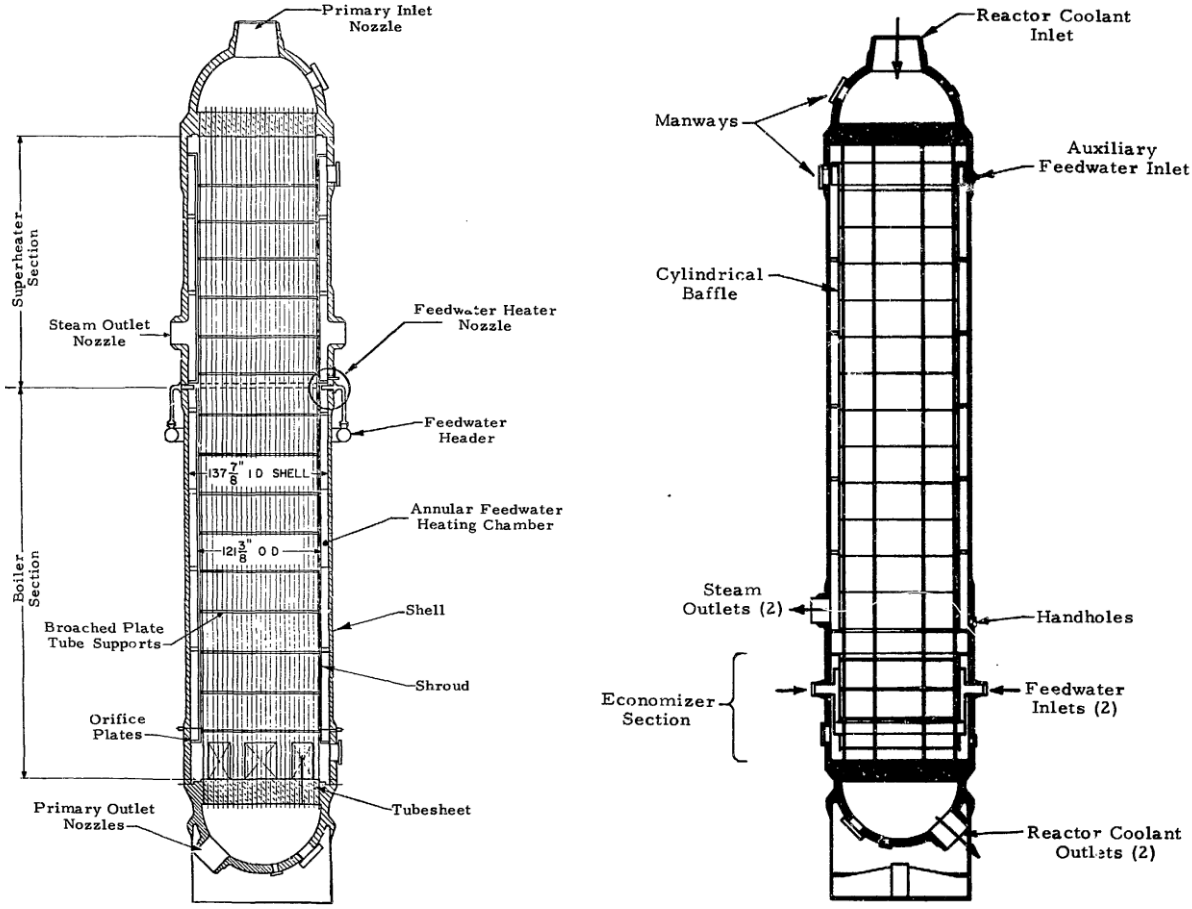
1. Introduction

As an important step in the Roadmap to Fusion Electricity, European Union (EU) is performing a pre-conceptual design study of a Demonstration fusion power plant (DEMO), [1]. The reactor should demonstrate the capability of producing few hundred MWs of net electricity while operating with a closed-tritium fuel cycle. The Breeding blanket (BB) is one of the key reactor components. It accomplishes several functions such as cooling device, tritium breeder (ensuring reactor self-sufficiency) and neutron shield. Different BB concepts were selected to be investigated in the DEMO R&D strategy. Among them, there is the Water-Cooled Lithium-Lead (WCLL), [1], that is the option under study in the current work. The WCLL blanket is constituted by two main subsystems: the breeder zone (BZ) and the first wall (FW). Each one is provided with an independent cooling circuit, called Primary Heat Transfer System (PHTS). The former removes the thermal power generated in the BZ by the interactions between the lead-lithium (liquid breeder) and the neutrons coming from the plasma. The latter cools the FW component, heated up by the incident heat flux and by the neutron wall load. The thermal power removed by BZ and FW PHTS is directly driven to the Power Conversion System (PCS) for its conversion into electricity, [2]. Heat transfer between PHTSs and PCS takes place within two steam generators (per circuit). Once-Through Steam Generators (OTSG) were selected for this application, [2]. Even if this is the first time such technology was proposed for nuclear fusion applications, OTSGs has been used and operated for decades in the field of nuclear fission power plants, in particular in Pressurized Water Reactors (PWR) [3]. In such environment, a full thermal-hydraulic characterization of the steam generator was already available, [3][4][5]. In the framework of EUROfusion Work Package Balance of Plant (WPBOP), at the Department of Astronautical, Electrical and Energy Engineering (DIAEE) of Sapienza University of Rome, a simulation activity was performed to evaluate the thermal-hydraulic behavior of this fundamental component during DEMO normal operations, considering that the pulsed plasma regime significantly jeopardizes the OTSG performances. To reach this goal, a full model of the component was prepared by using a modified version of RELAP5/MOD3.3 system code. This new extended version was developed at DIAEE, in collaboration with ENEA, to enhance the code capability in simulating fusion reactors, [6]. It is actually considered the reference code version to carry out the future simulation activity involving DEMO reactor.

2. Once-Through Steam Generators for DEMO application

2.1. General description of the component

The OTSG design foresees a straight-tube, straight-shell layout, with flat tubesheets and hemispherical primary heads. [3]. An overview of the OTSG design is shown in Figure 1a. Primary system is bounded by hemispherical heads, tubesheets and tube bundle. Primary coolant enters from the OTSG top and flows downwards, exiting from the component bottom. Secondary side is the steam-producing section. It is bounded by the shell, named vessel, the tube outer surface and the tubesheets. A cylindrical shroud, called riser, surrounds the tube bundle and channels the secondary flow along the thermal height. Subcooled feedwater enters the steam generator laterally, in the lower vessel (downcomer) section. Firstly, it is preheated by aspirating steam coming from the tube bundle region (recirculated flow). Then, secondary water moves through the annular downcomer. It reaches the vessel bottom in nearly saturated conditions. Later, it rises in the central shroud where it boils to dry steam and then it is superheated. Once reached the top, steam is turned by the tubesheet and directed to the annulus between riser and vessel, in the OTSG upper section. Here, it flows downwards to the two outlet nozzles, connected laterally. Starting from the shroud bottom, as feedwater is converted to superheated steam, three heat transfer regions can be identified: Nucleate Boiling Region (NBR), Film Boiling Region (FBR) and SuperHeat Region (SHR), [3]. The former is where saturated feedwater begins to boil. Tube outer surface remains wetted while small bubbles rapidly form and break away from it. Thanks to the turbulence due to bubble formation, this heat transfer mode ensures a high heat transfer coefficient (HTC). For this, most of the primary-to-secondary thermal exchange occurs in the NBR. The nucleate and forced convective boiling continue until enough water is vaporized and the liquid layer is replaced by steam on the surface of the tubes. Therefore, film boiling occurs at high qualities after the dry-out point and fully develops within a very short axial distance. In the film boiling heat transfer, the heat flux is sharply reduced and heat transfer occurs by convection through the steam and evaporation of entrained liquid droplets in the saturated core. At FBR top, only dry steam is present. In the final SHR, thermal power transferred from primary fluid is used to produce superheated steam. The evolution of OTSG technology consists in the Integral Economizer Once-Through Steam Generators (IEOTSG), [3]. The IEOTSG is a true once-through steam generator, without recirculation in the secondary side. Feedwater is admitted near the bottom of the component. In the central riser, it is quickly preheated to saturation while dry steam is obtained at about the same elevation as in the OTSG. Once reached the upper tubesheet, superheated steam is diverted downwards through the annulus between riser and vessel. Differently from OTSG, outlet nozzles are installed in the lower part (slightly above the inlet ones) to maintain a high temperature of the shell. In the IEOTSG, a further region can be identified in addition to the ones already described for OTSG. It is located at the shroud bottom and called economize region. Here, the subcooled liquid is rapidly heated and brought to saturation temperature. Its extension is reduced since it is characterized by high HTCs in both primary and secondary sides. The IEOTSG design is reported in Figure 1b.



(a) **(b)**

Figure 1. Design overview of OTSG **(a)** and IEOTSG **(b)** technologies, [3].

2.2. PHTS OTSGs pre-conceptual design

Regarding the OTSGs to be installed in DEMO BB PHTS, their design is still at a pre-conceptual stage, [2]. Such design was scaled from existent units still operating in nuclear fission power plants. Steam generator rated power was used as scaling factor. OTSG technology was considered to be appropriate to be installed in PHTS circuits since the primary (PHTS itself) and secondary (PCS) sides water thermodynamic conditions are comparable with respect to the ones of a PWR. Indeed, PHTS water enters the OTSGs (i.e. exits from the BB) at 601 K and it is cooled down to 568 K. Primary pressure is 15.5 MPa. On the secondary side, feedwater is admitted at 511 K and PCS reference pressure is set to 6.41 MPa. The main design data are reported in Table 1, for both BZ and FW steam generators. The connection between riser and vessel, allowing the recirculation, is located at nearly 60% of the thermal height.

Table 1. Pre-conceptual design parameters for BZ and FW OTSGs, [2].

Parameter	Unit	BZ OTSG	FW OTSG
Number of units (per PHTS)	-	2	2
Rated Power	MW	742	220
Number of tubes	-	7569	2197
Thermal height	m	12.99	12.99
Tube outside diameter	mm	15.88	15.88
Tube thickness	mm	0.89	0.89
Pitch to diameter ratio	-	1.28	1.28
Lattice	-	square	square
Vessel external diameter	m	2.9	1.5

2.3. RELAP5 model

As stated in section 2.2, even if rated power is quite different, BZ and FW OTSGs have the same pre-conceptual design rationale. Thus, steam generators of both primary cooling systems are supposed to have similar thermal-hydraulic (TH) performances during DEMO normal operations. A preliminary analysis on the BZ OTSG was already performed, [6][7]. For this reason, the current simulation activity focuses on the FW OTSG. A TH model of the component was prepared by using RELAP5/MOD3.3 system code. Its schematic view is shown in Figure 2. The same vertical mesh was adopted for the control volumes of all the RELAP5 components simulating the OTSG primary and secondary sides. Primary side was modelled with two branches, representing the inlet and outlet hemispherical heads, and an equivalent pipe component simulating the tube bundle. The PHTS hot leg was also included in the input deck. Inlet PHTS water thermodynamic conditions (temperature and mass flow, section 2.2) were set as boundary conditions (BCs). OTSG secondary side was simulated with four equivalent pipes, corresponding to lower/upper annular downcomer sections and to lower/upper central shroud sections. Three branches were used to link these pipe components, to manage the connections with the feedwater and steam lines and to simulate the recirculated flow. Feedwater line was added to the input deck by means of a dedicated pipe component. Steam lines were modelled up to the Turbine Stop Valves (TSV in Figure 2) and equipped with Safety Relief Valves (SRV in Figure 2). PHTS water temperature at blanket inlet (i.e., OTSG outlet) is a strict DEMO requirement. As a preliminary tentative, a temperature control system was associated to PCS feedwater. A Proportional-Integral (PI) controller was implemented to regulate the heat transfer inside the steam generator by tuning the secondary flow. In this way, the right PHTS temperature is obtained at OTSG outlet and the compliance to DEMO requirement is ensured. Control strategy for the steam generator will be refined and adapted once defined in the framework of the WPBoP research activity. Instead, feedwater inlet temperature (see section 2.2) was set as boundary condition. RELAP5 heat structures were used to simulate the thermal transfer taking place within steam generator, as well as the component heat losses. They also allow to account for the OTSG steel inventory (i.e., thermal inertia). Finally, what is worth to be emphasized are the correlations used by RELAP5 code to evaluate the heat transfer coefficient in both primary and secondary sides, [8]. If single-phase fluid is present, i.e. PHTS side and PCS side when feedwater is subcooled and steam is superheated, Dittus-Boelter correlation is adopted, [9]. Chen correlation is used for the nucleate boiling, [10], while Bromley model is implemented for the film boiling, [11]. The dryout quality is calculated by using the Groeneveld look-up tables, [12].

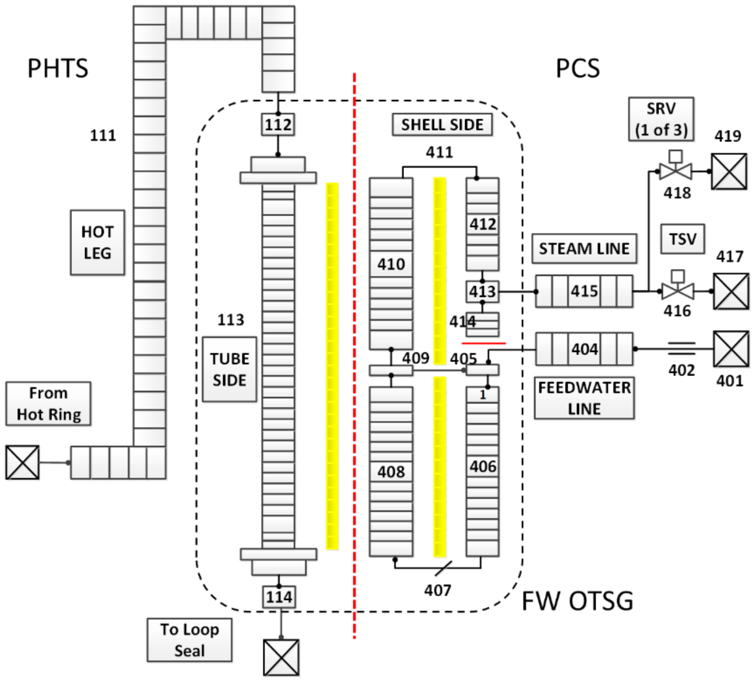


Figure 2. Schematic view of RELAP5 model developed for FW OTSG.

3. Results

3.1. Boundary conditions

Initially, the RELAP5 model discussed so far was used to preliminary assess the FW OTSG TH performances during pulse phase of DEMO normal operations. The current steam generator design, described in section 2.2, was tested in order to demonstrate its cooling capability with respect to BB and PHTS circuit. Standard procedure foresees that primary and secondary inlet conditions are imposed and the thermal power exchanged is checked. This procedure cannot be applied in the current simulation activity. In fact, during DEMO pulse, BB power and inlet/outlet temperatures (so also the mass flow) are strict requirements. For this, in the calculations performed, primary side inlet conditions are set while the PHTS water outlet temperature is monitored by the PI controller acting on the OTSG secondary flow (see section 2.3). Being all the primary side parameters set or controlled, also the steam generator exchanged power is imposed. On the secondary side, feedwater inlet temperature is a boundary condition since it depends on the feedwater preheaters train installed in the PCS upstream the OTSG. The parameters to be checked as simulation outcomes are the secondary and recirculation mass flows, as well as the steam outlet temperature.

3.2. Sensitivity analysis to assess the OTSG Model

Firstly, mesh and time step sensitivities were performed on the TH model presented in section 2.3. Thermal height (see Table 1) was divided in 20, 30 and 50 control volumes. A time step of 10^{-3} s was adopted. Incrementing the mesh number, the code predicts a higher steam outlet temperature (587, 589.3 and 590.6 K respectively) and, consequently, a lower secondary flow (116.2, 115.7, 115 kg/s). The mesh refinement also produces a decrease of recirculation inside the component (9.3, 8.9, 8.1 kg/s). These minor differences in the results are due to the precision in the assessment of the heat transfer regions within the steam generator (discussed in section 2.1). With a coarser mesh (20 control volumes), the NBR length is slightly overestimated. This increases the average HTC on the secondary side, that is the one limiting the overall steam generator heat transfer coefficient. To clarify this point, Figure 3 reports the primary/secondary side HTCs and the wall conductivity (computed as tube thermal conductivity, k, on tube thickness, s) against the normalized thermal height for the 30-mesh model. The normalized thermal height is considered going from the riser bottom to top. Primary side HTC and wall conductivity are nearly constant along the steam generator. Instead, secondary side HTC is of the same order of magnitude of the other two only up to the dryout occurring. In the residual length, corresponding to FBR plus SHR, the heat transfer between primary and secondary sides is strongly reduced. By increasing the mesh number, the model accuracy in predicting the effective height where dryout occurs is enhanced, even if the benefit is modest, as demonstrated by the small differences in the calculation outcomes. In conclusion, the 30-mesh model was selected to simulate the steam generator thermal height. With this nodalization, a time step sensitivity was carried out by varying this parameter from 1 x 10^{-4} s to 1 x 10^{-3} s. The results obtained by simulations do not change, either globally or locally. For this reason, they were not included in the paper and 10^{-3} s was the time step chosen to continue the computational activity. A further simulation was run by taking into account the RELAP5 additional model named Reflood, [8]. It was used to evaluate the 2D-conduction effect inside the tube wall. Without it, the system code performs 1D computations considering the wall conduction in the radial direction only. Instead, activating the Reflood, also axial conduction is taken into account. Secondary side HTC is the one mostly affected by the model activation. As shown in Figure 4a, the main effect to be detected is the increase of the peak before the dryout occurrence. Locally, the exchanged power rises significantly. Globally, the Reflood activation provokes a slight heat transfer increment, consisting in a higher steam outlet temperature (589.3 to 591 K) and a lower secondary flow (115.7 to 115.3 kg/s). In the following, to conservatively evaluate the steam generator TH performances, it was chosen to not consider this model.

3.3. Scoping calculations on DEMO pulse phase

Once selected the best settings for the FW OTSG model, several calculations were run to investigate the component design in different operative conditions, such as Beginning of Life (BoL) and End of Life (EoL), as well as to study alternative solutions. Simulations performed are collected in Table 2.

Table 2. DEMO pulse phase: main features related to calculations performed.

	Design Features				**Simulation Outcomes**		
ID	OTSG/ IEOTSG	BOL/ EOL	PCS pressure [MPa]	Feedwater Inlet Temp. [K]	Feedwater Mass Flow [kg/s]	Rec. Mass Flow [kg/s]	Steam Out Temp. [K]
C1	OTSG	BOL	6.41	511	115.7	8.9	589.3
C2	OTSG	EOL	6.41	511	121.4	6	565.9
C3	IEOTSG	BOL	6.41	511	115.8	-	589.1
C4	OTSG	BOL	6.00	507	113	9.6	593.1
C5	OTSG	BOL	6.80	515	120.1	5.4	579.6

To simulate the OTSG operative conditions at EoL, both tube fouling and plugging must be considered. The first reduces the overall heat transfer coefficient by adding two thermal resistances, related to deposits affecting tube internal and external surfaces; the second diminishes the heat transfer surface by postulating that a certain fraction of the total tube number is plugged and not available for thermal exchange. Primary/secondary deposit thermal resistances (0.5/1 x 10^{-5} m^2K/W) were derived from literature, [13][14], and set according to engineering judgment, while the target value for tube plugging (10%) was a design data for the OTSG, [2]. The heat exchange degradation, affecting the OTSG when passing from BoL (C1) to EoL (C2), is clearly visible in Figure 4b, comparing the secondary side HTC in both conditions. The main detectable effects are the appearance of an economize region at the bottom of the riser and the increase of the height where dryout takes place. To remove the steam generator rated power, at EoL, the control system strongly increments the PCS feedwater flow, provoking a significant reduction of the steam outlet temperature (compare cases C1 and C2 in Table 2). This is done to augment the secondary side velocity field and partially supply to the HTC drop due to the additional thermal resistances. At the elevation where the recirculation occurs, the steam quality at EoL is lower with respect to BoL and this reduces the recirculated contribution (see Table 2).

As stated before, IEOTSG design represents the evolution of the OTSG technology, [3]. The TH model described in section 2.3 was rearranged in order to match the peculiarities of the IEOTSG layout (see section 2.1). The main differences between models consist in the elimination of the junction allowing the secondary side recirculation flow (situated at 60% of the thermal height) and the location of the feedwater/steam inlet/outlet nozzles near the bottom of the component. The two different solutions were preliminary compared by considering only the thermal-hydraulic performances. The aim was to evaluate if IEOTSG technology could enhance the heat transfer between primary and secondary sides and so represent an interesting alternative to be studied for DEMO applications. Simulation outcomes are collected in Table 2, where case C1 refers to OTSG while C3 for IEOTSG. From the TH point of view, only small discrepancies can be observed between the two options. The main difference concerns the presence of an additional heat transfer region, the economize one, at the bottom of IEOTSG (see Figure 4c). Its length is quite reduced due to the high HTCs and the height corresponding to the dryout occurrence is nearly the same for both steam generator solutions. Figure 4c confirms the IEOTSG design features discussed in section 2.1. Thus, during DEMO pulse phase, the two technologies have a quite similar thermal-hydraulic behavior. However, further analyses must be performed to assess other technical aspects, for example the thermomechanical response.

Focusing again on the reference OTSG design, what is worth to be further investigated is the steam generator TH response to a modification in the PCS thermodynamic conditions. Secondary side pressure was increased and decreased with respect to the reference value (see Table 2). In every calculation, the feedwater inlet subcooling was kept, i.e. inlet temperature was modified proportionally to the saturation temperature. As shown by results contained in Table 2 (compare cases C1 and C4) and the secondary side HTCs reported in Figure 4d, decreasing PCS pressure produces a heat transfer increment within the component. In fact, steam exits the OTSG at higher temperature, lower secondary flow is required to remove the rated power and the height where dryout shows up is reduced. The prevalent effect influencing the steam generator performances is the increase of the primary/secondary side temperature difference in the NBR, where the majority of the thermal exchange takes place. The opposite OTSG behavior can be observed when PCS pressure is increased (compare cases C1 and C5 in Table 2 and secondary side HTC trends in Figure 4d).

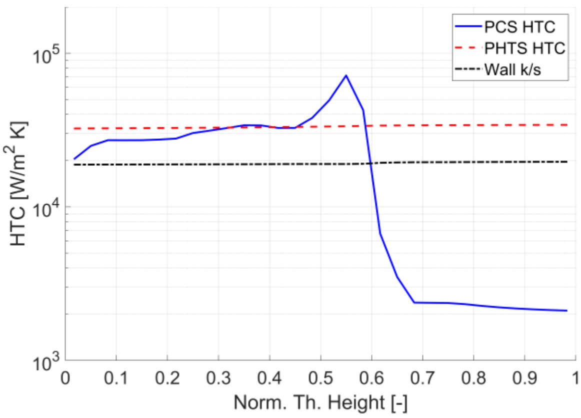


Figure 3. DEMO pulse phase, steam generator primary/secondary side HTCs and wall conductivity vs normalized thermal height (30-mesh model).

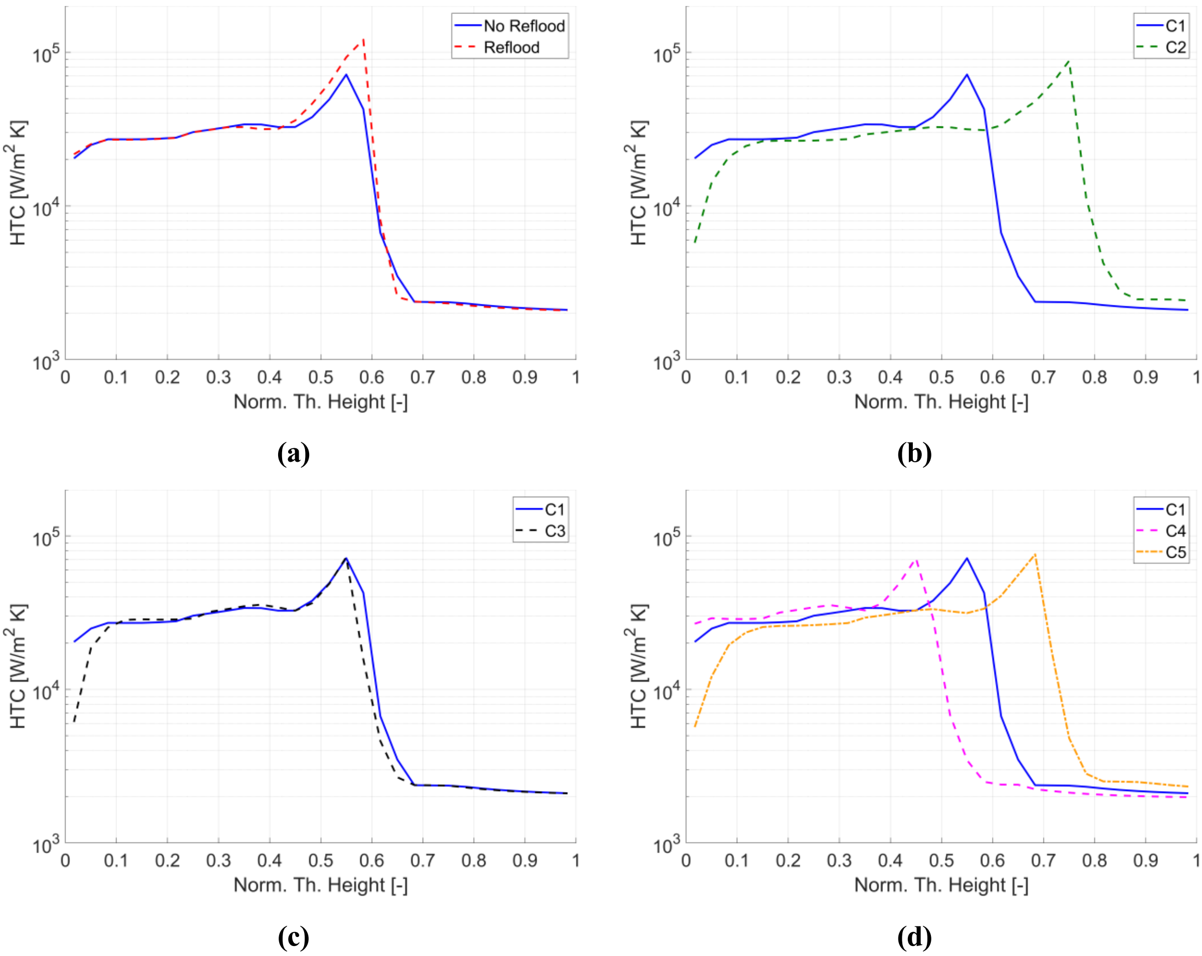
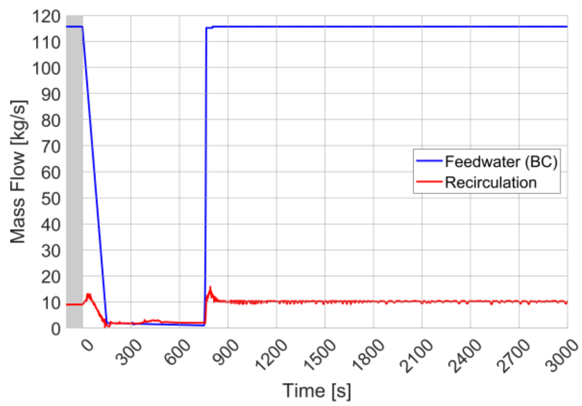


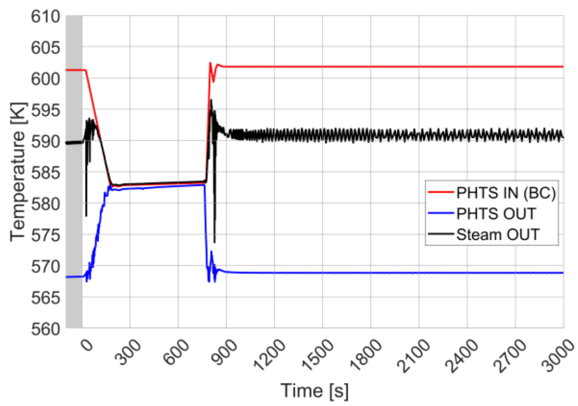
Figure 4. DEMO pulse phase, steam generator secondary side HTC vs normalized thermal height, comparison between simulation results: no Reflood vs Reflood **(a)**; OTSG at BoL (C1) vs EoL (C2) **(b)**; OTSG (C1) vs IEOTSG (C3) **(c)**; Different OTSG design for PCS pressure of 6.0 (C4), 6.41 (C1) and 6.8 MPa (C5) **(d)**.

3.4. Transient analysis on DEMO normal operations

Finally, FW OTSG behavior was evaluated during the overall DEMO normal operations, including both pulse and dwell phases. The reference plasma regime is composed by 2 hours of flat-top at full power, alternating with 10 minutes of dwell time. Power is ramp-down and ramp-up in nearly 100 s. During dwell time, only decay heat is still produced in the blanket, corresponding to nearly 2% of the reactor rated power. As for DEMO requirement, the BZ and FW primary pumps are always kept running at nominal velocity, in both pulse and dwell. Furthermore, during the latter, PHTS circuits must be operated at the system average temperature (nearly 583 K). A transient calculation was run by using case C1 (see Table 2) as initial condition. Plasma ramp down starts following 100 s of flat-top full power (grey background in Figure 5a to Figure 5d). Time was reset at the beginning of plasma ramp down, after which computation was run for 3000 s. According to DEMO requirement, a constant PHTS mass flow (equals to the one of pulse phase) was imposed for the overall simulation. Plasma ramp down and ramp-up were simulated by setting a variable BC for the PHTS temperature at OTSG inlet. To correctly simulate the feedback from BB, this boundary condition was derived from a previous analysis performed with a full model of the blanket and PHTS circuits, [7]. Although, in that case, OTSGs are present only in BZ primary circuit, as already discussed in section 2.3, the same TH behavior is expected for steam generators of both BZ and FW systems. For this reason, the BC derived from the study in [7] was considered appropriate for the current calculation. Finally, the PI controller acting on PCS feedwater was disabled. At its place, a variable trend was imposed (see Figure 5a). As preliminary tentative, a linear decrease and increase were adopted in correspondence of the plasma ramp down and ramp-up timing. During dwell, feedwater flow is kept at nearly 2% of the pulse value. In this way, the heat transfer within the steam generator is enough degraded to avoid PHTS overcooling and keep the primary system temperature at its average value, as for DEMO requirement. The appropriateness of this approach is demonstrated by PHTS outlet temperature trend shown in Figure 5b. Regarding the steam, two temperature peaks can be detected during pulse/dwell and dwell/pulse transitions (Figure 5b). These increases are rather limited (less than 5 °C in both cases) and do not cause concerns to the turbine operation. They are due to the temperature trend adopted as boundary condition for PHTS water at OTSG inlet (red line in Figure 5b, [7]). During ramp-down, the latter decreases slower with respect to the feedwater flow trend (blue line in Figure 5a). This delay is caused by the blanket thermal inertia, properly simulated in [7] and reported in the current work thanks to the specific boundary condition adopted. Instead, during ramp-up, PHTS inlet temperature rises faster with respect to feedwater flow. This depends on the particular shape of the plasma ramp-up curve adopted in [7]. It foresees a first sharp power increase, concentrated in the first few dozens of seconds, followed by a time interval where the power level is stabilized around the nominal value. The effect is a sudden rise in the PHTS inlet temperature, faster than the linear trend used for feedwater flow. However, in the future developments of the simulation activity, feedwater flow trend will be tuned to smooth these spikes. For example, it can be a little postponed in the pulse/dwell transition and slightly anticipated for the plasma ramp-up. What is worth to be noticed is that the liquid water inventory in the steam generator runs out during dwell time, as witnessed by Figure 5c. It shows the collapsed levels in the secondary side riser and lower downcomer, normalized with respect to the height of the components. During dwell, the OTSG is full of steam and this leads the secondary HTC to drop (Figure 5d), strongly limiting the overall heat transfer. This allows to keep the primary system temperature stable at the average value, as required.



(a)



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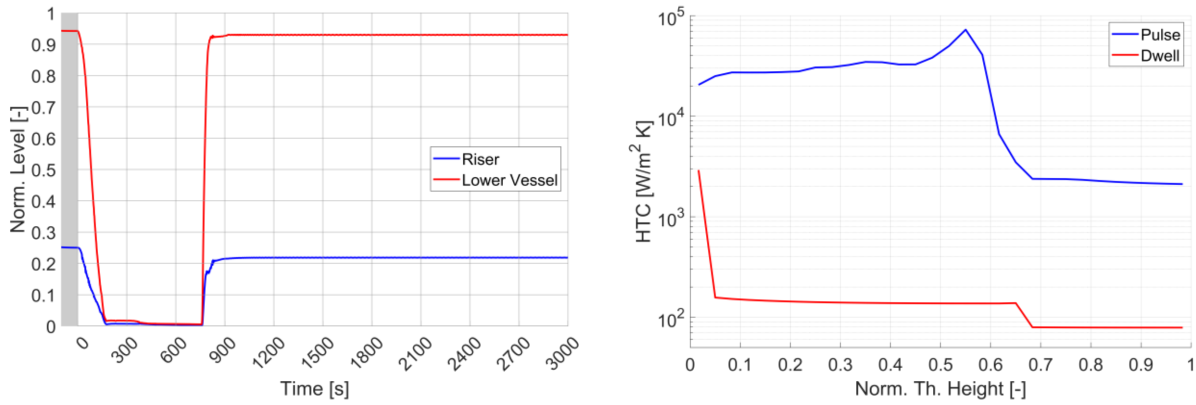

(c) (d)

Figure 5. FW OTSG main parameters during DEMO pulse and dwell phases: feedwater and recirculation flow rates **(a)**; main temperatures **(b)**; collapsed levels in the secondary side riser and lower downcomer **(c)**; secondary side HTC (comparison between pulse and dwell) **(d)**.

4. Conclusions

The pre-conceptual design of FW OTSG was assessed during DEMO normal operations by using a TH model developed with RELAP5/MOD3.3. Initially, the pulse phase was considered. The OTSG reference design was investigated in both BoL and EoL, individuating the main effects on the steam generator TH performances produced by the heat transfer degradation due to tube fouling and plugging. Then, OTSG and IEOTSG layouts were compared. Although, in IEOTSG, an additional heat transfer region (economize) is foreseen at the secondary side, no sensible differences in the global parameters were highlighted. Furthermore, it was studied the OTSG TH response to variations of the PCS thermodynamic conditions. A decrease/increase of the secondary system pressure produces an increment/reduction of the heat transfer within the component. Finally, a transient simulation was run to verify the OTSG capability to respect the DEMO requirements related to pulse/dwell transition and viceversa. A very preliminary management strategy (i.e. variable trend) for feedwater flow was proposed and analyzed. The simulation outcomes confirmed the capability of the FW steam generator to operate the primary system at a constant average temperature, as for DEMO requirement.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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