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Thermal-hydraulic modeling and analyses of the water-cooled EU DEMO using RELAP5 system code

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The conceptual design of the Primary Heat Transfer System (PHTS) of the water-cooled European (EU) DEMO foresees two independent cooling circuits, the breeding zone PHTS and the first wall PHTS. During the pulse time (120 minutes) the first delivers thermal power to the turbine, the latter delivers thermal power to the Intermediate Heat Transfer System (IHTS) equipped by an Energy Storage System (ESS). The IHTS delivers partially thermal power to the turbine in pulse so that to accumulate a suitable amount of energy in ESS to operate the turbine during the dwell time (10 minutes) at almost constant load, despite the EU DEMO pulsation of the generated thermal power. A dynamic model of the primary systems of water-cooled EU DEMO is developed using RELAP5/Mod3.3 system code to verify components sizing and to investigate code predictive capabilities. The model includes the primary and secondary side of the breeding zone and first wall, and in particular: in-vessel (i.e. breeding blanket) and ex-vessel components (i.e. main collectors, hot and cold legs, heat exchangers, steam generators, pumps). Preliminary assessments of the nodalization have been carried out, in particular checking pressure drops along the systems and heat exchanger performances.

Keywords: EU DEMO, PHTS, WCLL, RELAP5, BoP

1. Introduction

The main function of the PHTS of the water-cooled EU DEMO [1]-[4] is to provide cooling water to the first wall and blanket systems and to transfer the thermal power to the Power Conversion System (PCS) for its conversion into electricity. Considering the pulsed operation of DEMO, the Balance of Plant (BoP) includes the ESS with HITEC molten salt as secondary fluid, ensuring that the turbine works continuously during the dwell time [5].

Within this framework a research activity was conducted to validate components design of the water-cooled PHTS, IHTS and PCS design and to assess the predictive capabilities of RELAP5/Mod3.3 code in simulating relevant thermal-hydraulic phenomena. In order to realize a dynamic model of the systems an expanded version of the code was developed to implement PbLi and HITEC properties and related heat transfer correlations [6]. A thermal-hydraulic model of primary and secondary side of the BZ and FW systems was developed with RELAP5/Mod3.3 code and preliminary verification of the nodalization has been performed, evaluating pressure drops in the system loops and heat exchanged.

2. BoP configuration for DEMO WCLL BB

The operational sequence of EU DEMO Power Plant is based on nine pulses per day with a burn time of two hours (power pulse). The current PHTS design is based on EU DEMO 2015 baseline with 18 sectors and foresees a dwell time of 10 minutes, because of optimization of central solenoid recharge time and vacuum pump performance.

The water-cooled PHTS is constituted by two independent primary systems: the Breeding Zone (BZ) PHTS and the First Wall (FW) PHTS [5]. The main components of PHTSs (BZ and FW) are: the sector collectors and distributors, the loop collectors and distributors, the steam generators and heat exchangers, the hot and cold legs, the pressurizers and pumps. One loop per system is foreseen. Main components of each loop are symmetrically located with respect the radial-poloidal direction of the tokamak, at about 71 m from each other. A scheme of the overall BoP is shown in Fig. 1.

During the pulse mode (120 minutes), the BZ primary system delivers the power (1483.2 MW_{th}) to the steam turbine by means of two Once Through Steam Generators (OTSG). The thermal power removed by each OTSG is 741.6 MW_{th}, considering that the primary coolant inlet and outlet temperature are 295.0 °C and 328.0 °C, respectively, at 15.50 MPa, the corresponding mass flow rate is 3830.0 kg/s, calculated using RELAP5 water properties [9]. The OTSG secondary side (water) pressure is assumed 6.41 MPa and the feedwater coolant inlet temperature is 238.0 °C. The objective is to produce super-heated steam at 299.0 °C. Therefore, the feedwater flow for each OTSG is fixed at 404.0 kg/s.

During the pulse time the FW primary system delivers 439.8 MW_{th} of power to the ESS through two Intermediate Heat Exchangers (IHXs) with HITEC molten salt as secondary fluid. The power transferred through each intermediate heat exchanger is 219.9 MW_{th}. The reference configuration assumes the

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temperature cycle 295.0-328.0 °C for the primary water coolant system and 280.0-320.0 °C for the intermediate molten salt coolant system. The horizontal IHX is a typical liquid-liquid heat exchanger tube and shell with two passes. Pressurized water coolant flows inside U-shape tubes, in counter current direction with respect to the molten salt, which flows shell side with a cross flow path.

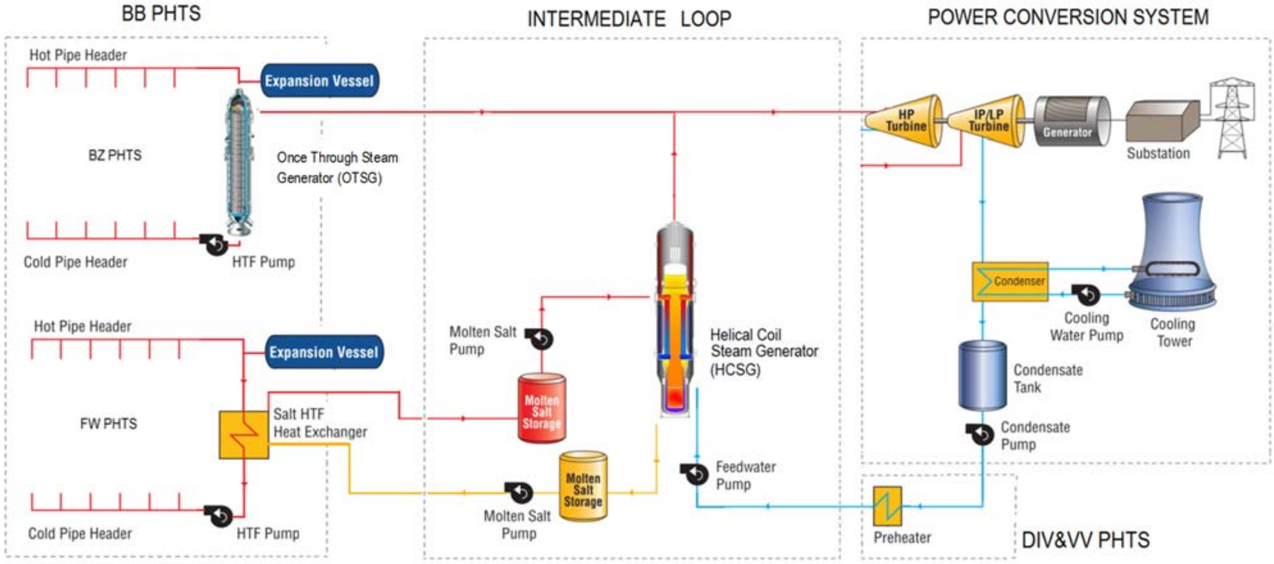

Fig. 1. Scheme of the BoP of the water-cooled EU DEMO.

Considering both the BZ and FW PHTS, six Main Coolant Pumps (MCPs) are foreseen in the current preliminary PHTS design of DEMO: four MCPs, two per loop, in the cold legs of the BZ PHTS, two MCPs in the FW PHTS. According with the main design data of the PHTS and considering the pressure drops in the in-vessel components, the overall pressure drops in the systems are 1.066 MPa and 1.018 MPa respectively in the FW and BZ PHTSs. Considering a postulated efficiency of 78%, the power consumed by each pump is 2.106 MW and 3.391 MW, respectively for those installed in the FW PHTS and in the BZ PHTS.

Taking into account that the total power from Blanket (BZ and FW) is 1923 MW_{th} and the power from auxiliary systems (Vacuum Vessel and Divertor) is 337.3 MW_{th}, which is used to pre-heat feedwater of the PCS, the average power available in pulse and dwell (turbine power) is 2086.4 MW_{th}. In order to keep constant the turbine power during pulse and dwell time, a fraction of FW PHTS thermal energy is stored in the ESS during pulse time and transferred from ESS to PCS during dwell. The energy stored in the ESS is equal to 1.25×10^6 MJ, which corresponds to a thermal power of 173.9 MW_{th}. The difference between the FW PHTS total power (439.8 MW_{th}) and the power stored in the ESS (173.9 MW_{th}) is directly delivered to the PCS during pulse time and it is equal to 265.9 MW_{th}.

During pulse time, the energy is transferred from the ESS to the PCS through one Helical Steam Generator (HCSG). The hot molten salt flows in shell side and transfers energy to water flowing in the tubes side. The molten salt temperature cycle is 280.0-320.0 °C. The feedwater enters in the HCSG with an inlet temperature of 238.0 °C and exits with an outlet temperature of 299.0 °C at 6.41 MPa. During pulse, the mass flow rate of HITEC of one HCSG is 4266.0 kg/s, and the feedwater mass flow rate, calculated with the enthalpy balance, is 145.1 kg/s.

During the dwell time (10 minutes), four HCSG deliver power from ESS to PCS, considering the same boundary conditions of pulse mode (i.e. IHTS and PCS fluids temperature and pressure), for each steam generator the HITEC and feedwater mass flow rate is 8344.7 kg/s and 284.2 kg/s, respectively. Taking into account that, the mass flow of molten salt from hot to cold tanks is 33436 kg/s, the ESS contains a mass of molten salt equal to 20062 tons, thus the volume necessary to store this amount of molten salt is about 11000 m^3 for both hot and cold tanks.

3. RELAP5/Mod3.3 PHTSs nodalization

In order to develop a dynamic model of the systems, an extended version of RELAP5/Mod3.3 code has been set-up with the implementation of the PbLi and HITEC fluid proprieties [5][6], as well as the following heat transfer correlations: 1) Sieder Tate correlation [7] for the convective heat transfer wall-HITEC in the FW PHTS heat exchanger shall side; and 2) Zukauskas correlation [8] for the heat transfer wall-HITEC in the IHTS helical-coil steam generators.

A thermal-hydraulic model of the FW and BZ PHTSs have been developed using RELAP5/Mod3.3 system code [9].

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- The FW primary system includes the in-vessel and ex-vessel components of the primary side and the secondary side which is constituted by the molten salt intermediate system.
- The BZ primary system includes the in-vessel components and the ex-vessel components of the primary side and the secondary side.

The common features adopted for the RELAP5/Mod3.3 input deck in both systems are:

- "sliced approach", applied in the nodalization;
- elevations of the various parts of the plant are maintained in the nodalization;
- K-loss coefficients in junction are evaluated or estimated on the basis of geometries;
- roughness is set 3.2e-5 m in all components apart from the IHX tubes where is 4.0e-6 m.

The in-vessel components of both FW and BZ systems are modeled with an equivalent PIPE component, one per sector and per system, of 75 axial volumes. The first 30 axial volumes represent the inlet feeding pipes and manifolds, thus the flow area is the total area of three outboard and two inboard pipes, and a hydraulic diameter which is the average diameter between inboard and outboard pipes. The tubes and channels of the breeding blanket region are modeled with 15 axial volumes with a total flow area equal to the area of one channel multiplied for the number of channels in one segment and for the total number of segments (two inboard and three outboard). The hydraulic diameter is the diameter of one BZ tube (0.008 m) in the BZ system and the diameter of one FW channel (0.007 m) in the FW system. A scheme of the FW in-vessel components is reported in Fig.2.

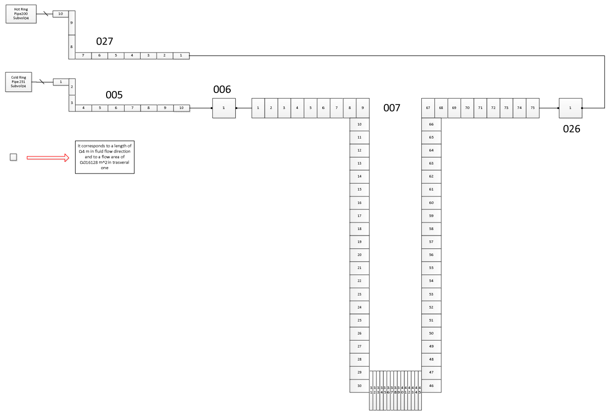
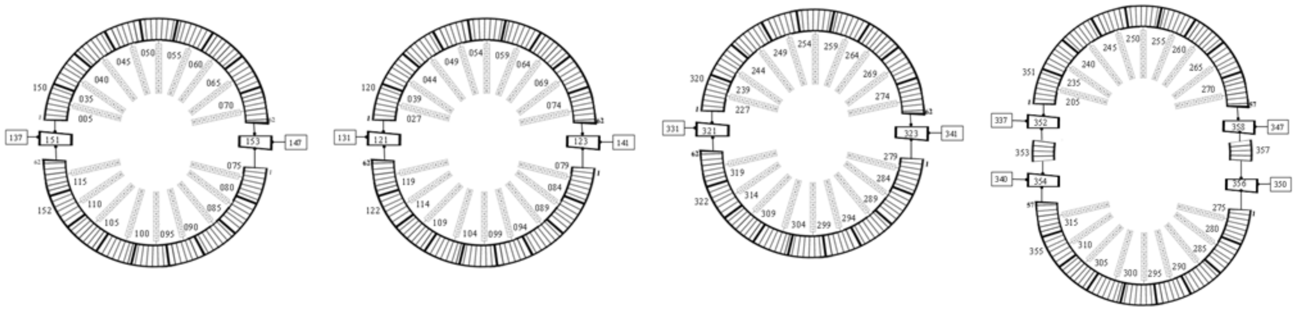


Fig. 2. BZ and FW in-vessel nodalization scheme.

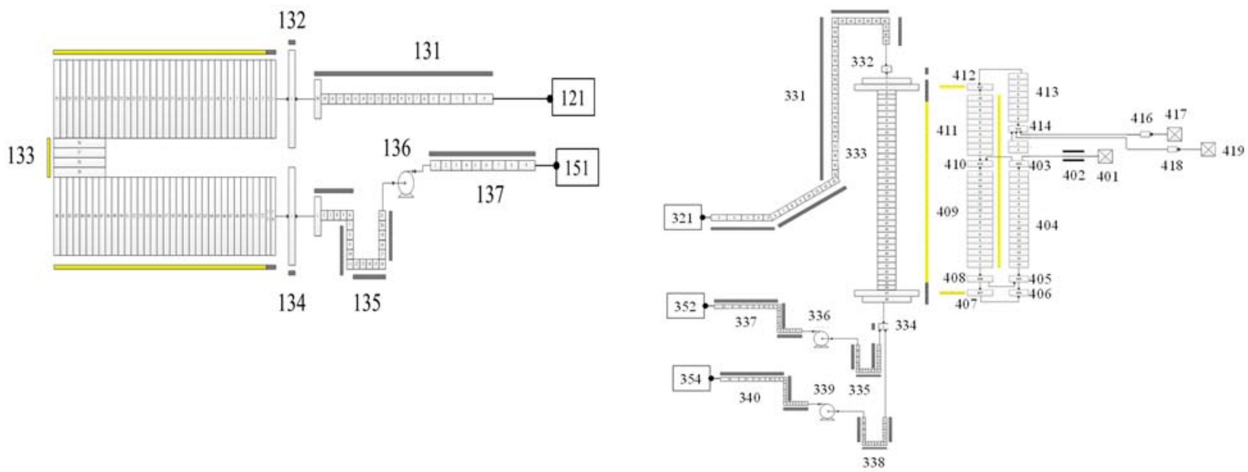


a) FW PHTS sectors distributors and cold ring

b) FW PHTS sectors collectors and hot ring

c) BZ PHTS sectors collectors and hot ring

d) BZ PHTS sectors distributors and cold ring



e) FW PHTS IHX, hot and cold legs

f) BZ PHTS OTSG, hot and cold legs

Fig. 3. RELAP5/Mod3.3 nodalization of BZ and FW PHTS.

The ex-vessel components (i.e. collectors, distributors, rings, hot and cold legs) are modeled with PIPE components with proportion 1:1 to the real geometry. The tubes of the OTSGs and IHX are modeled with equivalent pipes with hydraulic diameter of one tube (0.014148 m) and flow area of one tube multiplied for the number of tubes (7569 and 5211, respectively for each OTSG and IHX). A scheme of the nodalization of FW and BZ components is reported in Fig.3.

Inlet and outlet boundary of secondary side of both systems were set using TIME DIPENDENT VOLUME and TIME DEPENDENT JUNCTION components.

Thermal structures are used to model the heat exchange between primary and secondary side of FW and BZ PHTSs and to simulate the heat extracted by the breeding blanket (FW and BZ).

4. RELAP5 preliminary analyses and results

Steady-state simulations have been run to analyze the FW and BZ PHTS systems operative point during Pulse mode. The results given by RELAP5 have been used to qualify the nodalization, comparing the pressure drops at nominal steady state with the theoretical one in the primary systems (FW and BZ). Moreover, the code has been applied to check the correctness of the sizing of OTSG and water/HITEC IHX.

Steady state solutions were achieved for the FW and BZ systems. The pressure drops of the primary systems were evaluated and compared with the theoretical pressure drops. The pressure drops were calculated using the Colebrook correlation [10] for the friction factor and evaluating the concentrated pressure losses (i.e. elbow, abrupt area change). The results show a good accordance between theoretical values and RELAP5 values, with minor differences observed in the BZ PHTS in the hot section of the system, as evidenced in Fig. 4 and Fig. 5, where pressure drops of FW PHTS and BZ PHTS are reported, respectively.

The calculated steady state results show that the power extracted by each IHX in the FW system is greater than the reference value (219.9 MW_{th}), which determines a greater ΔT in both primary and secondary side, as evidenced from results reported in Tab.1. As regard the OTSGs of the BZ system, the results show a relative difference between reference values and RELAP5 results of the order of magnitude of 1%, as shown in Tab.2.

Table 1. FW HEX steady state parameters.

Parameter	Units	Ref. value	Relap5/Mod3.3 Value
Power	MW	219.9	222.4
PHTS mflow	kg/s	1135.8	1184.5
HITEC mflow	kg/s	3524.3	3524.3
PHTS inlet temp	°C	328.0	327.9
PHTS outlet temp	°C	295.0	295.8
HITEC in. temp	°C	280.0	280.0
HITEC out. temp	°C	320.0	320.5

Table 2. BZ OTSG steady state parameters.

Parameter	Units	Ref. value	Relap5/Mod3.3 Value
Rated Power	MW	741.6	748.2
PHTS mflow	kg/s	3830.6	3864.7
Feedwater mflow	kg/s	404.0	404.3
PHTS inlet temp	°C	328.0	325.7
PHTS outlet temp	°C	295.0	292.2
Feedwater in. temp	°C	238.0	238.0
Feedwater out. temp	°C	299.0	301.0

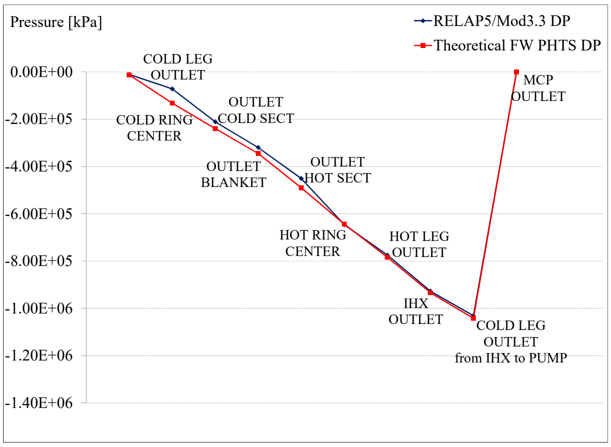


Fig. 4. FW PHTS pressure drops .

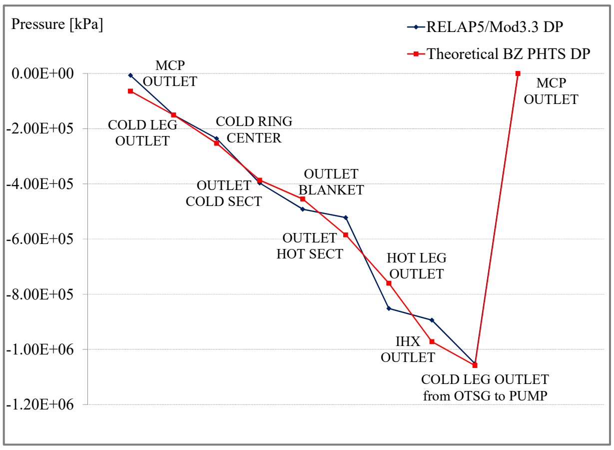


Fig. 5. BZ PHTS pressure drops.

5. Conclusions

Within the framework of the EUROfusion WPBoP, a research activity was conducted to validate component design using the thermal-hydraulic system code RELAP5/Mod3.3, to assess the predictive capabilities of the code in the domains of interest and to investigate thermal-hydraulic performances of the water-cooled EU DEMO PHTS.

The main achievements can be summarized as follows:

- The configuration of the PHTS, the IHTS/ESS and the PCS are defined. The main components (i.e. SG, HEX, pumps) are sized and rely on existing technologies.

- TH SYS model of the PHTSs has been developed using RELAP5/Mod3.3 code. The model includes the in-vessel and ex vessel components of the primary side and the secondary side of the FW PHTS and BZ PHTS.
- Preliminary verifications on RELAP5 nodalization (i.e. pressure drops and heat exchange) show that the code has the capability of simulating FW and BZ PHTSs and related main components.
- The thermal-hydraulic model will be used to perform system analyses to evaluate pros and cons of water-cooled DEMO PHTS and PCS.
- A future development of the present work is the simulation of the entire DEMO operating regime, considering also the switching transients from Pulse to Dwell and vice versa.

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