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Design and analysis of the improved configuration of the secondary circuit for the EU-DEMO power plant

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DEMO is planned to be a prototype fusion power plant capable of demonstrating production of electricity at the level of a few hundred MW. DEMO is considered to be an intermediate step between the ITER experimental reactor and a commercial power plant. Design and assessment studies on the European (EU) DEMO are carried out by the EUROfusion consortium. The Primary Heat Transfer System (PHTS) transfers heat from the breeding blanket (BB) and other reactor heat sources (divertor and vacuum vessel) to the secondary circuit. Two main BB concepts, and the respective PHTSs, for EU-DEMO are considered: the Helium Cooled Pebble Bed (HCPB) BB and the Water Cooled Lithium Lead (WCLL) BB. Two variants for each concept are possible: with or without the Intermediate Heat Transfer System (IHTS), including the Energy Storage System (ESS), between the PHTS and the Power Conversion System (PCS), which generates electrical energy. The role of IHTS and ESS is to prevent energy pulses removed by BB PHTS during the plasma burns to be directly transferred to PCS. In 2017 we proposed the first concept of the PCS configuration for the option WCLL BB with the ESS, which ensured almost constant production of electricity during both plasma pulse and dwell phases. However, we observed some disadvantages of this concept, e.g., excessive temperature differences between the pulse and dwell phases in several heat exchangers. In the present paper, we develop the GateCycle model of the improved PCS configuration for the WCLL BB with the ESS option, which ensures almost constant production of electricity during both plasma pulse and dwell phases, as well as acceptably small temperature fluctuations $|T_{pulse} - T_{dwell}|$ in all the circuit components, which should prevent their failure due to excessive thermal stress.

Keywords: Eu-DEMO, Power Conversion System, Water-Cooled Lithium-Lead Breeding Blanket, Energy Storage System, GateCycle

1. Introduction

A DEMOnstration Fusion Power Plant (DEMO) is planned to be a prototype power plant capable of demonstrating production of electricity from fusion at the level of a few hundred MW and operating with a closed tritium fuel-cycle [1]. DEMO is considered to be an intermediate step between the ITER experimental reactor and a commercial fusion power plant. Design and assessment studies on the European (EU) DEMO are carried out by the Power Plant and Technology Department of the EUROfusion consortium [2,3].

According to the current baseline design, the reference EU DEMO operation scenario includes 3600 s of plasma burn pulse and 600 s of dwell period [3]. The EU DEMO power plant consists of two main heat transfer systems. The Primary Heat Transfer Systems (PHTS) transfer thermal power from the breeding blanket (BB) and other reactor heat sources (divertor and vacuum vessel) to the secondary circuit called Power Conversion System (PCS) which generates electrical energy [4]. Two main BB concepts, and the respective PHTSs, for EU DEMO are considered: the Helium Cooled Pebble Bed (HCPB) BB [5] and the Water Cooled Lithium Lead (WCLL) BB [6]. Two variants for each concept are possible: with or without the Intermediate Heat Transfer System (IHTS), including the Energy Storage System (ESS) based on the molten salt (MS) tank, between the PHTS and the PCS. The role of IHTS and ESS is to prevent energy pulses removed by BB PHTS during the plasma burns to be directly transferred to PCS, so that thermal energy was provided to PCS in a smooth, continuous way, guarantying system components lifetime. In 2017 the first concept of the PCS configuration for the option WCLL BB with the ESS was proposed, which ensured almost constant production of electricity during both plasma pulse and dwell phases [6,7]. However, we observed a disadvantage of the PCS circuit considered in [7], namely excessive temperature fluctuations between the plasma pulse and dwell phases in several heat exchangers, which could cause their failure due to thermal fatigue. In the present paper we propose the detailed GateCycle (GC) model of the new improved configuration of the steam/water PCS for the option WCLL BB with the ESS [8] and we study its operation during the plasma burn pulse (nominal operating conditions) and during the dwell phase.

2. Model assumptions

The conception of the considered PCS cycle was developed by its designers in [8]. In this work we present its improved version, shown schematically in Fig. 1, obtained after some refinements of operating parameters. The proposed PCS utilizes heat from the BB, Divertor (DIV) and Vacuum Vessel (VAC VES). BB is

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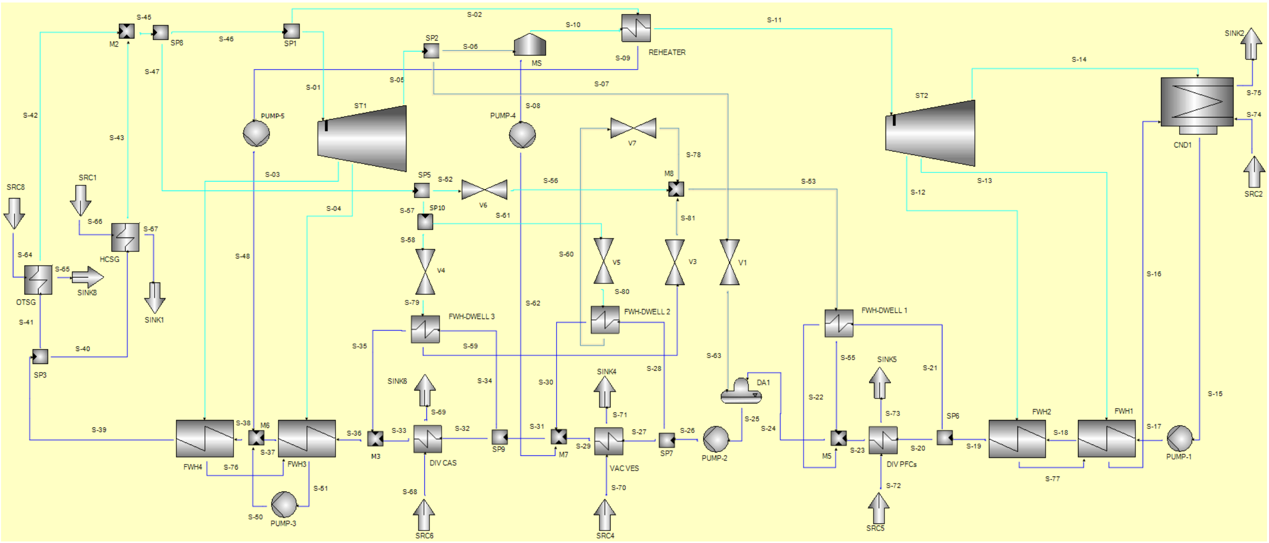

Fig. 1. Scheme of our GC model of the EU DEMO PCS for the option WCLL BB PHTS with ESS.

Table 1. Parameters of the selected streams during the plasma burn pulse and during the dwell phase.

Stream	From	To	PULSE				DWELL			
			$\dot{m}$ (kg/s)	p (MPa)	T (ºC)	quality, x	$\dot{m}$ (kg/s)	p (MPa)	T (ºC)	quality, x
S-01	SP1	ST1	873.6	6.410	298.0	1	886.1	6.410	299.0	1
S-03	ST1	FWH4	41.4	3.600	244.2	0.9749	48.7	3.600	244.2	0.9758
S-04	ST1	FWH3	41.4	2.650	227.1	0.9469	43.4	2.600	226.0	0.9462
S-05	ST1	SP2	790.8	1.000	179.9	0.8847	794.0	0.998	179.8	0.8853
S-06	SP2	MS	785.9	1.000	179.9	0.8847	783.2	0.998	179.8	0.8853
S-10	MS	Reheater	695.3	1.000	179.9	1	693.3	0.998	179.8	1
S-11	Reheater	ST2	695.3	1.000	273.0	1	693.3	0.998	273.4	1
S-12	ST2	FWH2	35.4	0.080	93.5	0.9480	35.6	0.080	93.4	0.9483
S-13	ST2	FWH1	36.5	0.040	75.9	0.9188	35.9	0.040	75.8	0.9191
S-14	ST2	CND1	623.4	0.005	32.9	0.8464	621.8	0.005	32.9	0.8467
S-15	CND1	Pump-1	695.3	0.005	32.9	0	693.3	0.005	32.9	0
S-18	FWH1	FWH2	695.3	0.320	60.3	0	693.3	0.320	59.9	0
S-20	SP6	DIV PFC	693.9	0.320	86.2	0	7.6	0.320	86.1	0
S-23	DIV PFC	M5	693.9	0.320	132.6	0	7.6	0.320	128.6	0
S-21	SP6	Dwell-1	1.4	0.320	86.2	0	685.7	0.320	86.1	0
S-22	Dwell-1	M5	1.4	0.320	110.3	0	685.7	0.320	132.3	0
S-24	M5	DA1	695.5	0.320	132.5	0	857.3	0.320	129.9	0
S-25	DA1	Pump-2	700.4	0.320	135.8	0	868.2	0.320	135.8	0
S-27	SP7	Vac Ves	699.0	6.500	136.6	0	8.6	6.501	136.6	0
S-29	Vac Ves	M7	699.0	6.500	165.3	0	8.6	6.501	160.0	0
S-28	SP7	Dwell-2	1.4	6.500	136.6	0	859.6	6.501	136.6	0
S-30	Dwell-2	M7	1.4	6.500	153.2	0	859.6	6.501	165.8	0
S-32	SP9	DIV Cas	789.4	6.500	167.0	0	9.6	6.501	167.2	0
S-33	DIV Cas	M3	789.4	6.500	200.2	0	9.6	6.501	194.6	0
S-34	SP9	Dwell-3	1.6	6.500	167.0	0	948.5	6.501	167.2	0
S-35	Dwell-3	M3	1.6	6.500	203.6	0	948.5	6.501	201.0	0
S-36	M3	FWH3	791.0	6.500	200.2	0	958.0	6.501	201.0	0
S-37	FWH3	M6	791.0	6.500	220.9	0	958.0	6.501	219.1	0
S-38	M6	FWH4	952.9	6.500	221.1	0	1130.3	6.499	220.0	0
S-41	SP3	OTSG	807.9	6.500	236.9	0	8.1	6.499	235.6	0
S-42	OTSG	M2	807.9	6.500	297.9	1	8.1	6.499	296.2	0
S-40	SP3	HCSG	144.9	6.500	236.9	0	1122.2	6.499	235.6	0
S-43	HCSG	M2	144.9	6.498	299.1	1	1122.2	6.499	299.1	1
S-45	M2	SP8	952.9	6.410	298.0	1	1130.3	6.410	299.0	1
S-46	SP8	SP1	952.7	6.500	298.0	1	966.3	6.410	299.0	1

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cooled with two separate cooling circuits: one for the blanket First Wall (FW) and one for the Breeding Zone (BZ). Heat from the BB BZ is utilized to produce steam in the Once Through Steam Generator (OTSG), whereas heat from the BB FW is gathered in the MS tank (not included in our model) and used to produce steam in the Helical Coil Steam Generator (HCSG). Heat extracted from VAC VES and from DIV (cooled with two cooling circuits: one for the Plasma Facing Components (PFC) and one for the Cassette (Cas)) is used to preheat feed water in the respective heat exchangers (HXs). It is assumed that during the dwell phase most of thermal power is provided to the circuit from the MS tank via HCSG, whereas thermal power of all the reactor sources decreases down to the level of their decay heat (1% of the nominal value for each source). Three additional HXs, namely: FWH-Dwell 1, FWH-Dwell 2 and FWH-Dwell 3, are used to compensate the dwell power reduction of HXs DIV PFC, VAC VES and DIV CAS, respectively. Some thermal power is provided to HXs FWH-Dwell 1-3 also during the plasma pulse, in order to reduce temperature fluctuations $|T_{pulse} - T_{dwell}|$ in these components. The limiting temperatures of the considered PCS cycle are assumed 328 ºC (hot inlet of OTSG) and 20 ºC (cooling water inlet at the condenser CND1) [7,8].

In the initial part of our analysis, aimed at the preliminary design and sizing of the main circuit components, we developed a convergent GC model (in the "Design" mode) of the whole considered PCS circuit. As a second stage, a number of "Off-design" (with the fixed design of all the circuit components) cases of this model were created, in which the operational parameters were gradually changed until they reached the values corresponding to the dwell phase. These simulations were performed in order to demonstrate the feasibility of safe plant operation and to estimate the cycle power and efficiency during the pulse and the dwell phases. The design calculations of turbines were performed using the Spencer Cotton Cannon efficiency method with the set values of extractions flow rates and pressures. For off-design calculations of turbines, we used: the isentropic expansion efficiency method with the fixed input bowl and extraction pressure values. For deaerator (DA1), operation at constant pressure and pegging steam control was chosen. Heat loss in heat exchangers was assumed to be 1% of the heat rate provided by the hot fluid. Pressure drop in pipes and in some HXs was not taken into account.

The gross electrical power output of the generator is calculated as:

$$W_{gross} = \eta_{gen}(W_{t1} + W_{t2}) \quad , \quad (1)$$

where $\eta_{gen} = 0.98$ [7] is the generator efficiency and W_{ti} is the shaft power of the i-th turbine. The electrical power of the considered cycle is defined as:

$$W_{cycle} = W_{gross} - \sum_{i=1}^{5} W_{pump\,i} \quad , \quad (2)$$

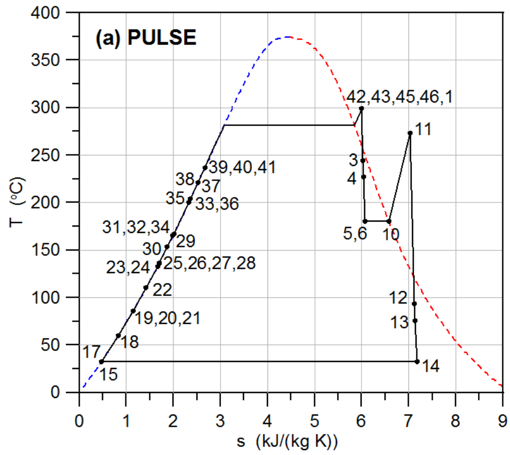
Where $W_{pump\,i}$ is the power consumed by the i-th pump in the circuit (which does not include pumps in PHTS and in MS tank). To calculate powers $W_{t\,i}$ and $W_{pump\,i}$ we use standard formulas and values of mechanical efficiencies specified in [9]. The thermal power supplied to the cycle is computed as:

$$\dot{Q}_{cycle} = \dot{Q}_{OT\,SG} + \dot{Q}_{DIV\,CAS} + \dot{Q}_{DIV\,PFC} + \dot{Q}_{VacVes} + \dot{Q}_{HC\,SG} \quad . \quad (3)$$

We assess the gross and cycle power and efficiency $\eta_x = W_x / \dot{Q}_{cycle}$ (x = *gross* or *cycle*) for the pulse and dwell phase separately, as well as their average values for the whole time of the cycle operation (weighted average with $t_{pulse} = 120$ min and $t_{dwell} = 10$ min serving as weights). It should be mentioned, however, that the W_{cycle} and η_{cycle} values refer only to our model (Fig. 1), which does not include pumps in the PHTS and IHTS as well as power consumption in the EU DEMO auxiliaries (magnet system, cryoplant, vacuum pumps, etc.). Thus, the actual net power and efficiency of the EU DEMO plant will be much lower than W_{cycle} and η_{cycle} estimated by us.

3. Results

The values of operating parameters in the main circuit components are presented in Table 1 and in the respective T-s diagrams in Fig. 2. It is seen that at both pulse and dwell operational modes the water / steam parameters in all the main PCS components are within the reasonable range, while the temperature fluctuations $\Delta T = |T_{pulse} - T_{dwell}|$ remain small (ΔT_{max} = 22 ºC in stream



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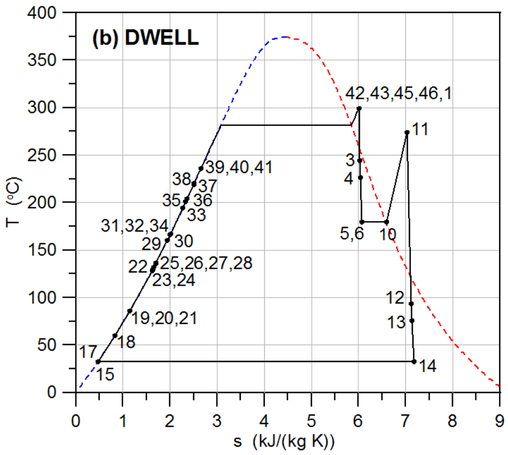

Fig. 2. T-s diagram for the considered cycle operating (a) during the plasma burn pulse, and (b) during dwell.

Table 2. Outcomes of power and efficiency calculations.

Parameter	PULSE	DWELL
$\dot{Q}_{OTSG}$ (MW)	1483.03	14.87
$\dot{Q}_{DIV\ CAS}$ (MW)	115.22	1.15
$\dot{Q}_{DIV\ PFC}$ (MW)	136.01	1.36
$\dot{Q}_{VacVes}$ (MW)	85.99	0.86
$\dot{Q}_{HCSG}$ (MW)	266.09	2071.58
$\dot{Q}_{cycle}$ (MW)	2086.34	2089.83
W_{t1} (MW)	259.05	264.12
W_{t2} (MW)	536.20	534.84
W_{gross} (MW)	779.35	782.99
W_{cycle} (MW)	772.00	774.18
η_{gross} (%)	37.35	37.47
η_{cycle} (%)	37.00	37.05

S-22, which is an acceptable value). This is an optimistic result, which may indicate the potential possibility of safe operation of the considered plant during both the plasma pulse and the dwell phases.

The values of thermal power provided to the cycle from all the EU DEMO heat sources, as well as the cycle power and efficiencies are compiled in Table 2. The electrical power and efficiency of the considered circuit averaged over the whole time of the cycle operation was assessed as W_{gross_av} = 779.63 MW, W_{cycle_av} = 772.16 MW, η_{gross_av} = 37.36%, η_{cycle_av} = 37.01%. It can be noticed, that the shaft power of both turbines, as well as electrical power output and efficiency of the plant are almost the same in both the pulse and the dwell phases, despite the pulsed thermal power production in the EU DEMO reactor. This advantageous feature is similar to the approach presented in [7], but in contrast to the earliest concept of the PCS for the WCLL BB with the ESS, in which the electrical power of the circuit was reduced during the dwell period down to about 50% of its nominal value [9].

4. Summary and conclusions

The detailed convergent GC model of the new, improved PCS configuration for the WCLL BB with ESS option of the EU DEMO plant has been elaborated. The model provided preliminary design and sizing of the main circuit components, which will help in their cost estimation. We used the model to simulate the PCS operation in steady state during both the plasma burn pulse and the dwell phase. It was demonstrated that the proposed PCS circuit is able to operate with almost the same gross electrical power of about 780 MW and gross efficiency of 37% during both phases. The temperature fluctuations $|T_{pulse} - T_{dwell}|$ in all components of the proposed PCS circuit remain acceptably small, which should prevent their failure due to excessive thermal stress. This is an improvement with respect to the previous iteration of the circuit discussed in [7].

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