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Design and analysis of a new configuration of secondary circuit of the DEMO fusion power plant using GateCycle

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Conceptual and design studies on the European DEMOnstration Fusion Power Plant (DEMO) are carried out under the lead of the EUROfusion Consortium. The Primary Heat Transfer System (PHTS) transfers heat from the nuclear heat sources, i.e. the breeding blanket, divertor, and vacuum vessel, to the secondary circuit called Power Conversion System (PCS) which generates electric energy. To mitigate undesirable transient effects resulting from the pulsed DEMO operation, the Intermediate Heat Transfer System (IHTS) with the Energy Storage System (ESS) filled with molten salt is added between the PHTS and PCS. One of the four considered options for the blanket cooling and the related PHTS is the Water-Cooled Lithium-Lead Breeding Blanket (WCLL BB). Recently new cooling concept for the WCLL BB has been proposed. This work is focused on the design of the new configuration of the steam/water PCS for the option WCLL BB with the ESS. The detailed GateCycle model of the considered circuit is created and its operation during the plasma burn and during the dwell phase is simulated. The proposed model of the PCS cycle is used to study the effect of the operating conditions on the cycle power and efficiency, and its basic operating parameters.

Keywords: fusion power plant, DEMO, Power Conversion System, Water-Cooled Lithium-Lead Breeding Blanket, GateCycle

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1. Introduction

Conceptual studies on the European DEMOnstration Fusion Power Plant (DEMO) are being conducted in Europe under the lead of the EUROfusion Consortium [1] as part of the EU Roadmap to Fusion Electricity [2], with the aim to demonstrate feasibility of electricity production at the level of a few hundred MW by the middle of this century. The Primary Heat Transfer System (PHTS) transfers heat from the DEMO nuclear heat sources, i.e. the breeding blanket, divertor, and vacuum vessel, to the secondary circuit called Power Conversion System (PCS) which generates electric energy. The reference DEMO operation scenario is based on the cycle 2 hr of plasma burn pulse and 30 min of dwell time [1]. One of the four considered options for the blanket cooling is the Water-Cooled Lithium-Lead Breeding Blanket (WCLL) [3]. Recently the new cooling concept for the WCLL BB as well as the related PHTS and PCS have been proposed [4-6]. This concept is based on the assumption that there are two separate cooling circuits for the blanket first wall (FW) and for the breeding zone (BZ). In addition, in order to increase the overall plant efficiency, the heat recovered from the vacuum vessel (VV) and from the divertor (DIV) - two cooling circuits: one for the DIV Plasma Facing Components (PFC) and one for the DIV cassette (CAS), is used to heat-up the feedwater in PCS. To mitigate undesirable transient effects resulting from the pulsed DEMO operation the Intermediate Heat Transfer System (IHTS) with the Energy Storage System (ESS) based on the molten salt (MS) tank is integrated between the PHTS and PCS.

The aim of the present work is to develop a detailed GateCycle (GC) model of the steam/water PCS cycle for the new configuration of the WCLL BB PHTS with the ESS option [7] and to analyze its operation at the nominal conditions (plasma burn pulse) and during the dwell period.

2. Model characterization

2.1 PCS model

The preliminary concept of the considered PCS cycle was proposed by its designers in [5]. Here we developed its more mature version, which is schematically shown in Fig. 1. The considered cycle utilizes heat provided from the breeding blanket (BB FW and BB BZ), from the divertor (DIV CAS and DIV PFCs) and from the vacuum vessel (VV). Heat extracted from the BB FW during the plasma pulse is accumulated in the MS tank. We assume that during the dwell period the thermal power of all the reactor heat sources (BB FW, BB BZ, DIV CAS, DIV PFCs, and VV) is reduced down to their decay heat level (assumed to be 1% of the nominal value for each source), while the most of thermal power is provided to the circuit from the MS tank via the steam generator (MS SG in Fig. 1). In the dwell phase, steam produced in MS SG feeds the HP turbine (ST1), the reheater, and two additional heat exchangers (HXs) FWH-Dwell 1 and FWH-Dwell 2 used to balance the HXs DIV PFCs, VV and DIV CAS power reduction. According to [5] the limit temperatures of the cycle are: 328 ºC (heating water inlet temperature at the SG BB BZ) and 20 ºC (cooling water inlet temperature at the condenser CND1). For design calculations of turbines, we used the Spencer Cotton Cannon efficiency method assuming the values of extractions flow rates and pressures. For off-design calculations of turbines, we used: the sliding inlet pressure method, Spencer Cotton

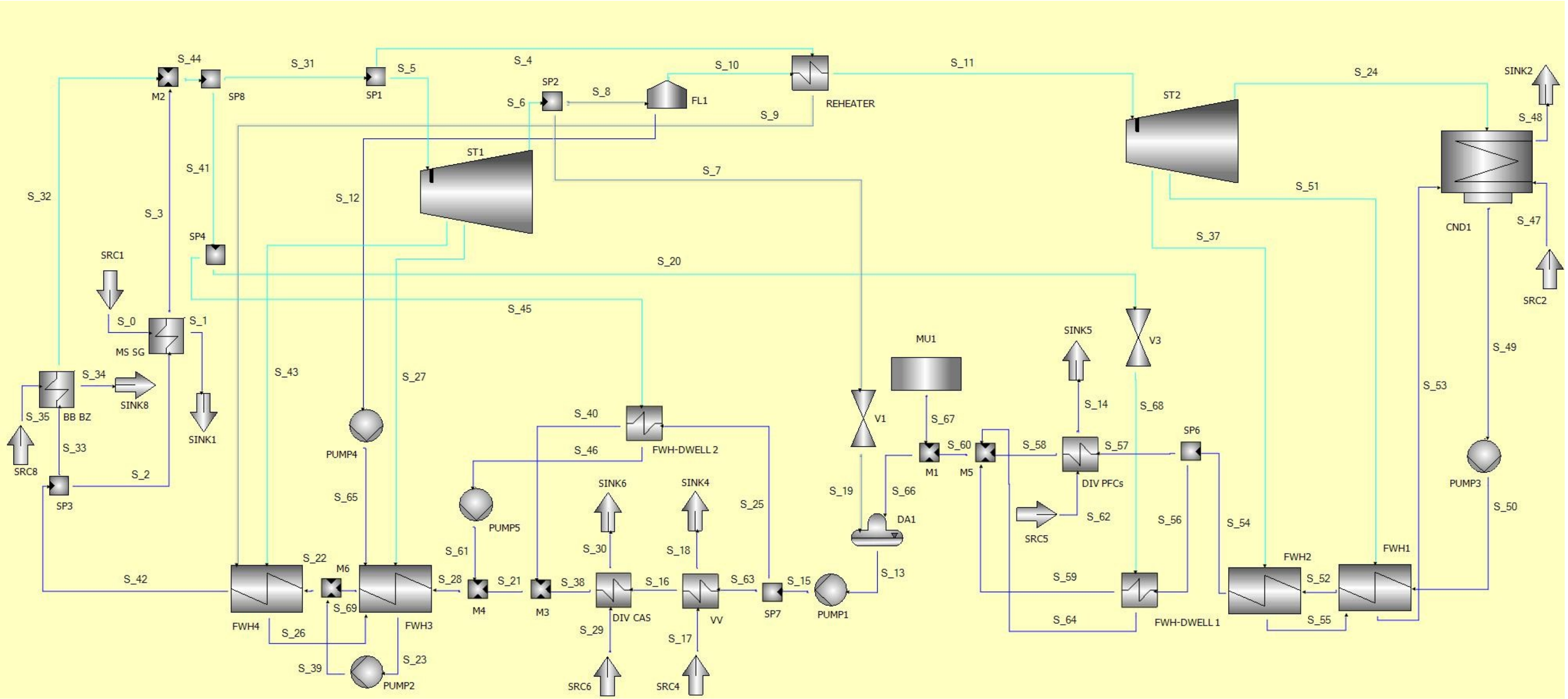


Fig. 1. Scheme of the considered general PULSE/DWELL GC model of the DEMO PCS (option WCLL BB PHTS with ESS).

Cannon efficiency method with Putman correction, and modified Stodola extraction pressure method. For deaerator, we applied operation at constant pressure and pegging steam control. We assumed heat loss in heat exchangers to be 1% of the heat rate provided by the hot fluid.

At first, two separate convergent GC models for the PULSE and for the DWELL phase were developed in the "Design" mode, which was aimed at the preliminary design and sizing of all the PCS components. In the PULSE model the circuit component operating at very low load during the plasma burn phase (MS SG, FWH Dwell 1 and 2) were considered "inactive" and thus were not taken into account. This allowed preliminary sizing of all the other PCS components. Analogously, the DWELL model provided the design and size of the MS SG, FWH Dwell 1 and 2 components.

Then we integrated both models into one general PULSE/DWELL GC model, shown in Fig. 1, by adding to the PULSE model the heat exchangers MS SG, FWH Dwell 1 and 2, for which we imported the design from the DWELL model. The dimensions of these HXs were not changed during further design works (they were set to "Off-design" mode). Next, the "Design" mode calculations for the pulse phase data were carried out. Finally, the "Off-design" case of this general model was used to perform calculations for the dwell phase. These simulations were aimed at demonstration of the feasibility of safe plant operation and providing information for further optimization of the circuit design, as well as at the assessment of the cycle power and efficiency during both phases.

2.2 Energy calculations

The gross electrical power produced by the generator is computed as:

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

(1)

where $W_{t\,i}$ is the shaft power of the *i*-th turbine and $\eta_{gen} = 0.98$ [5] is the assumed generator efficiency. We define the electrical power of the cycle as:

$$W_{cycle} = W_{gross} - \sum_{i=1}^{5} W_{pump_i},$$

(2)

where $W_{pump\,i}$ is the power consumed by the *i*-th pump in the considered circuit. The powers $W_{t\,i}$ and $W_{pump\,i}$ were computed in the same way as in [8]. The rate of heat provided to the cycle is calculated as:

$$\dot{Q}_{cycle} = \dot{Q}_{BB\,BZ} + \dot{Q}_{DIV\,CAS} + \dot{Q}_{DIV\,PFCs} + \dot{Q}_{VV} + \dot{Q}_{MS\,SG}$$

. (3)

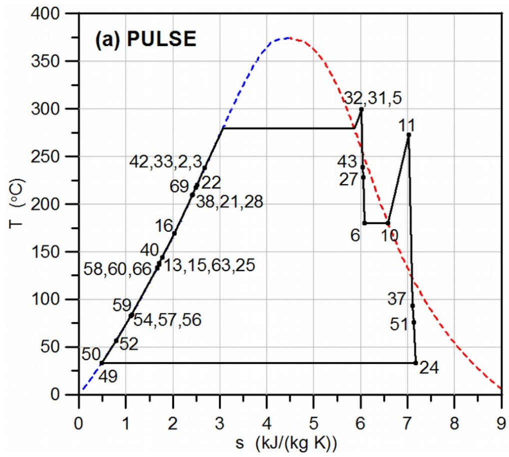
The evaluation of the cycle power and efficiency is done for the pulse phase, dwell phase and the weighted average. The weighted average gross and electrical efficiencies of the cycle for the whole time of the cycle operation are computed as:

$$\eta_{x\_av} = \frac{W_{x\_pulse} \cdot t_{pulse} + W_{x\_dwell} \cdot t_{dwell}}{\dot{Q}_{cycle\_pulse} \cdot t_{pulse} + \dot{Q}_{cycle\_dwell} \cdot t_{dwell}}, \quad (4),$$

where x = *gross* or *cycle*, t_{pulse} = 120 min and t_{dwell} = 30 min are the durations of the burn and dwell phase, respectively. It should be mentioned, however, that our model does not take into account the power consumed by the pumps in PHTS and IHTS, and by DEMO auxiliaries, such as e.g. the cryoplants, vacuum pumps, the magnet system, etc. Thus, the real net power of the DEMO plant and the respective net plant electrical efficiency will be much lower than W_{cycle} and η_{cycle} predicted by Eqs. (2) and (4).

3. Results

We obtained the convergent GC model (in the "Off design" mode) for the whole considered PCS circuit and at both the conditions corresponding to plasma pulse and to the dwell period. The main operating parameters of this model are gathered in Table 1, whereas the respective T-s diagrams are presented in Figs. 2. It can be noticed that at both operational modes the water / steam parameters in most of the PCS components remain within the reasonable range. This is an encouraging result indicating the potential feasibility of operation of the proposed PCS circuit during both the plasma pulse and the dwell period.



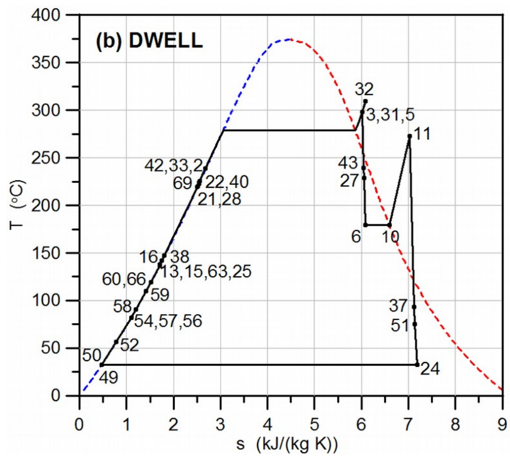


Fig. 2. T-s diagram for the considered cycle during the plasma pulse (a), and during the dwell phase (b).

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

Stream	From	To	PULSE				DWELL			
			$\dot{m}$ (kg/s)	p (MPa)	T (°C)	quality, x	$\dot{m}$ (kg/s)	p (MPa)	T (°C)	quality, x
S_5	SP1	ST1	767.9	6.376	299.5	1	759.0	6.310	297.9	1
S_43	ST1	FWH4	27.2	3.285	238.9	0.9703	14.1	3.316	239.5	0.9706
S_27	ST1	FWH3	19.7	2.692	227.9	0.9524	14.4	2.723	228.5	0.9528
S_6	ST1	SP2	721.1	0.997	179.8	0.8881	730.5	0.981	179.1	0.8868
S_8	SP2	FL1	715.8	0.997	179.8	0.8881	704.7	0.981	179.1	0.8868
S_10	FL1	Reheater	635.7	0.997	179.8	1	624.9	0.981	179.1	1
S_11	Reheater	ST2	635.7	0.998	273.0	1	624.9	0.981	272.6	1
S_37	ST2	FWH2	32.3	0.080	93.4	0.9481	31.6	0.078	93.0	0.9483
S_51	ST2	FWH1	28.6	0.040	75.8	0.9189	28.1	0.039	75.4	0.9191
S_24	ST2	CND1	574.8	0.005	32.9	0.8465	565.2	0.005	32.7	0.8469
S_49	CND1	Pump3	635.7	0.005	32.9	0	624.9	0.005	32.7	0
S_52	FWH1	FWH2	635.7	0.330	56.5	0	624.9	0.330	56.31	0
S_54	FWH2	SP6	635.7	0.330	82.4	0	624.9	0.330	82.1	0
S_57	SP6	DIV PFC	632.5	0.330	82.4	0	37.5	0.330	82.1	0
S_58	DIV PFC	M5	632.5	0.330	133.2	0	37.5	0.330	90.8	0
S_56	SP6	Dwell 1	3.2	0.330	82.4	0	587.4	0.330	82.1	0
S_59	Dwell 1	M5	3.2	0.330	84.0	0	587.4	0.330	109.8	0
S_66	M1	DA1	635.7	0.330	133.0	0	665.7	0.330	118.9	0
S_13	DA1	Pump1	641.0	0.330	136.8	0	691.4	0.330	136.8	0
S_63	SP7	VV	634.6	6.376	137.7	0	48.4	6.624	137.7	0
S_16	VV	DIV Cas	634.6	6.376	169.2	0	48.4	6.624	141.9	0
S_38	DIV Cas	M3	634.6	6.376	210.0	0	48.4	6.624	147.4	0
S_25	SP7	Dwell 2	6.4	6.376	137.7	0	643.0	6.624	137.7	0
S_40	Dwell 2	M3	6.4	6.376	144.1	0	643.0	6.624	225.4	0
S_28	M4	FWH3	641.1	6.376	209.4	0	820.4	6.624	219.2	0
S_69	FWH3	M6	641.1	6.376	217.1	0	820.4	6.624	222.7	0
S_22	M6	FWH4	858.0	6.376	220.1	0	1028.7	6.310	224.1	0
S_42	FWH4	SP3	858.0	6.376	238.0	0	1028.7	6.310	238.4	0
S_33	SP3	BB BZ	858.0	6.376	238.0	0	8.4	6.310	238.4	0
S_32	BB BZ	M2	858.0	6.376	299.5	1	8.4	6.310	309.3	1
S_2	SP3	MS SG	0.0009	6.376	238.0	0	1020.3	6.310	238.4	0
S_3	MS SG	M2	0.0009	6.376	238.0	0	1020.3	6.310	297.8	1
S_31	SP8	SP1	858.0	6.376	299.5	1	859.0	6.310	297.9	1

Table 2. *Results of power (in MW) and efficiency evaluation.*

	PULSE	DWELL
$\dot{Q}_{BB\ BZ}$	1577.03	15.71
$\dot{Q}_{DIV\ CAS}$	114.70	1.15
$\dot{Q}_{DIV\ PFC}$	135.96	1.36
$\dot{Q}_{VV}$	86.02	0.86
$\dot{Q}_{MS\ SG}$	0.00	1869.77
$\dot{Q}_{cycle}$	1913.72	1888.84
W_{t1}	233.34	234.2

W_{t2}	491.33	482.48
W_{gross}	710.18	702.35
W_{cycle}	703.21	695.38
η_{gross}	37.11%	37.18%
η_{cycle}	36.75%	36.82%

While developing the system regulation strategy we made some attempts to reduce as much as possible the temperature fluctuations $\Delta T = |T_{pulse} - T_{dwell}|$ in the circuit components, in order to minimize thermal stresses and prevent failure of HXs due to thermal fatigue. That is why during the pulse phase we provided small mass flow rates of steam and feed water to the HXs FWH-Dwell 1 (streams: S_56 and S_59) and FWH Dwell 2 (streams 25 and S_40), although in principle they were assumed to be inactive in this phase. However, it can be noticed in Table 1 (streams S_38 and S_40) that the ΔT values in HXs DIV CAS and FWH-Dwell 2 are unacceptably large. To cure this problem, we propose to modify the circuit in the next iteration of its design, by connecting the FWH-Dwell 2 in parallel with the HX VV only and add another HX FWH Dwell 3 connected in parallel with the HX DIV CAS. In such case, the steam stream S_45 should be split in order to feed both FWH – Dwell 2 and FWH – Dwell 3.

The values of thermal power supplied to the cycle from different reactor heat sources are compiled in Table 2. They agree very well with the respective values given in [5]. The electrical output and efficiency of the considered circuit averaged over the whole operation period is W_{gross_av} = 708.61 MW, W_{cycle_av} = 701.65 MW, η_{gross_av} = 37.12%, η_{cycle_av} = 36.76%. A striking advantage of the proposed circuit is the possibility to produce electricity at almost constant power despite the pulsed operation of the DEMO reactor. This is in contrast to the earlier concept of the PCS for the WCLL BB option in which the electrical output of the circuit was reduced during the dwell phase down to about 50% of its nominal value [8,9].

4. Summary, conclusions and perspectives

The thorough convergent GC model of the new PCS configuration for the WCLL BB with ESS option of the DEMO plant has been developed. The model was used to simulate the PCS operation during both the plasma pulse and the dwell period. The model provided preliminary sizing of the main circuit components which, after some refinement, will be used for their cost estimation. A modification of the circuit was proposed to avoid the excessive temperature fluctuations in some HXs (DIV CAS and FWH - Dwell 2). It was demonstrated that the proposed PCS circuit is able to operate with almost constant gross electrical power of about 700 MW and gross efficiency of 37% during the whole period of the DEMO cycle.

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