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Analysis of the secondary circuit of the DEMO fusion power plant using GateCycle

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HIGHLIGHTS

- A GateCycle model of the Power Conversion System for pulsed DEMO is presented.
- Operations at the nominal burn conditions and during the dwell period are studied.
- Possibility of safe reduction of the thermal power down to 50% is demonstrated.
- The obtained results can be utilized while sizing the DEMO Energy Storage System.

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ABSTRACT

Conceptual activities on the DEMO fusion power plant design are progressing in Europe under the lead of the EUROfusion Consortium. According to the current EU DEMO plant design, the Primary Heat Transfer System (PHTS) transfers heat from the nuclear heat sources, i.e. breeding blanket, divertor and (optionally) vacuum vessel, to the Power Conversion System (PCS) responsible for generating electric energy. To mitigate issues related to the pulsed DEMO operation, adding the Energy Storage System (ESS) filled with molten salt, between the PHTS and PCS, has been proposed. One of the four candidate options for the realization of the blanket and the related PHTS is the Water-Cooled Lithium-Lead Breeding Blanket (WCLL). In the present work a detailed GateCycle model of the DEMO PCS, for the option WCLL, with the ESS was created and its operation at the nominal conditions (plasma burn) and at the reduced heating power (dwell period) was studied. It was demonstrated, that during the dwell period the amount of heat provided from the ESS to the considered cycle can be safely reduced down to 50% of its nominal value. This is an important information for the ESS designers which should help in its proper sizing.

1. Introduction

ITER is planned to be the research type tokamak which will achieve the energy breakeven point. The next step towards the realization of fusion energy will be DEMO – the first demonstration fusion power plant producing grid electricity at the level of a few hundred MW. DEMO plant designers are required to maximize the conversion efficiency of the primary and secondary plant circuits. The Primary Heat Transfer System (PHTS) transfers heat from the nuclear heat sources, i.e. breeding blanket, divertor and (optionally) vacuum vessel, to the secondary circuit called Power Conversion System (PCS) responsible for generating electric energy. One of the four candidate options for the realization of the blanket and the related PHTS is the Water-Cooled Lithium-Lead Breeding Blanket (WCLL) [1,2]. According to the current EU DEMO baseline design, the DEMO reactor will produce thermal power in pulses lasting about 2 h interrupted by dwell periods of about half an hour [3]. To mitigate problems related with the pulsed operation of DEMO the Intermediate Heat Transfer System between the PHTS and PCS has been proposed, which includes the Energy Storage System (ESS) filled with solar molten salt [1]. Size of the ESS will depend on the heat demand of the PCS during the dwell phase.

The aim of the present work is to create a detailed GateCycle (GC) model of the steam/water PCS cycle for the WCLL option with the ESS and to analyze its operation at the nominal conditions (plasma burn) and at the reduced heating power (dwell period), for a possible reduction of the ESS dimensions.

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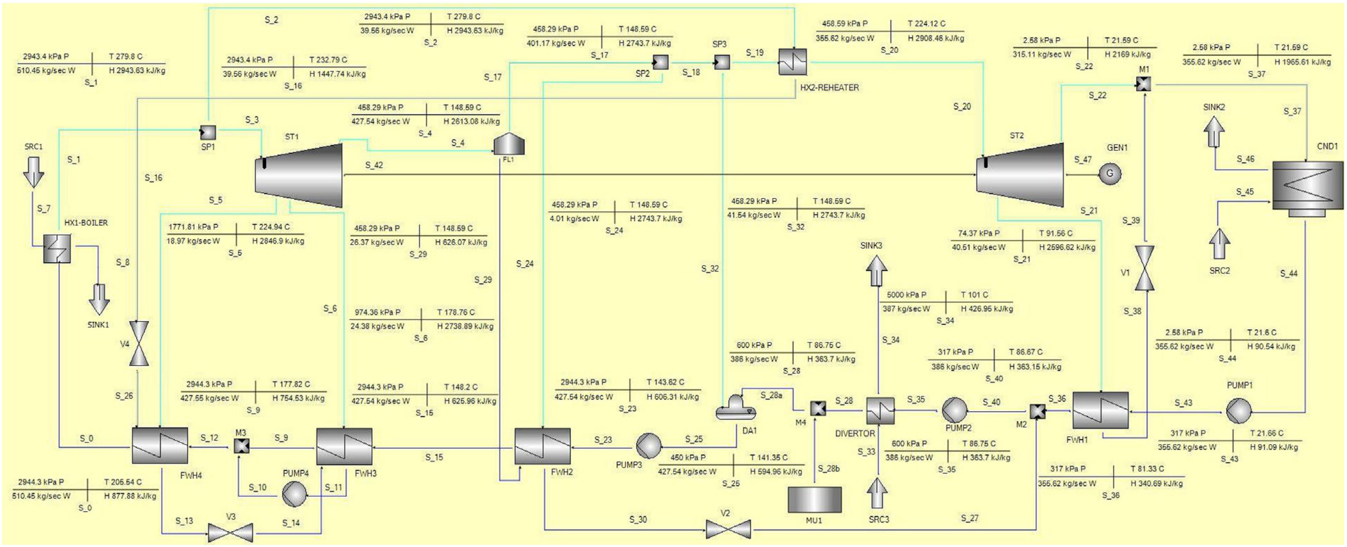

Fig. 1. Scheme of the considered GC model of the DEMO PCS and the values of the main streams parameters for its operation during the dwell period ($\dot{Q}_{DIV} = 0$MW, $\dot{Q}_B = 1065$MW, i.e. 50% of the nominal value).

2. Model description

2.1. Basic assumptions

The basic concept of the considered PCS cycle was proposed in Ref. [4]. Here we study its more refined version, which is schematically presented in Fig. 1. The proposed cycle utilizes heat provided from the breeding blanket via the ESS and from the divertor. As a first stage of our analysis operation at the nominal conditions is studied, aimed at the design of the PCS components. In the second stage, operation at the reduced thermal power is considered in the "off design" mode, i.e. with the fixed design of the circuit components. We assume that during the dwell phase thermal power provided from the ESS is gradually reduced down to 50% of its nominal value, whereas power of the divertor source immediately drops to 0. We also assumed that at the reduced power the considered PCS is operated under sliding-pressure control, while the turbines are modeled according to the Spencer-Cotton-Cannon off-design efficiency method with Putman correction and modified Stodola off-design extraction pressure method. According to Ref. [4], the maximum temperature in the circuit was assumed to be 280 °C, whereas the minimum temperature was assumed 32 °C in the nominal conditions, but was reduced down to 21.6 °C at the lowest considered thermal power.

2.2. Energy calculations

Shaft power of the i-th turbine ($i = 1, 2$) is computed as:

$$W_{t_i} = \eta_{tm} \left[\dot{m}_{in} h_{in} - \sum_{j=1}^{n_{se}} \dot{m}_{se_j} h_{se_j} - \dot{m}_{out} h_{out} \right], \tag{1}$$

where the number of steam extractions $n_{se} = 2$ for the HP turbine (ST1 in Fig. 1) and 1 for the LP turbine (ST2), respectively, h is the water specific enthalpy, and the mechanical efficiency of each turbine is assumed to be $\eta_{t_m} = 0.998$ [4]. The electrical power produced by the generator (gross power) is calculated as:

$$W_{gross} = \eta_{gen}(W_{t1} + W_{t2}), \tag{2}$$

where $\eta_{gen} = 0.97$ is the assumed generator efficiency [4,5]. The net electrical power of the cycle is defined as:

$$W_{cycle} = W_{gross} - \sum_{i=1}^{4} W_{pump_i}, \tag{3}$$

where W_{pump_i} is the power of the i-th pump:

$$W_{pump_i} = \dot{m}_{pump_i}(h_{out\,i} - h_{in_i})/\eta_{pump}, \tag{4}$$

where $\eta_{pump} = 0.934$ is the pump motor efficiency [6]. The rate of heat supplied to the cycle is computed from:

$$\dot{Q}_{cycle} = \dot{Q}_B + \dot{Q}_{DIV}, \tag{5}$$

where $\dot{Q}_B$ and $\dot{Q}_{DIV}$ is the rate of heat supplied from the blanket via the ESS (HX1 BOILER in Fig. 1) and from the divertor (HX DIVERTOR), respectively. At the nominal operating conditions $\dot{Q}_B = 2129$MW, whereas $\dot{Q}_{DIV} = 148$MW [4]. The gross and the net electrical efficiency of the cycle are calculated as:

$$\eta_{gross} = W_{gross}/\dot{Q}_{cycle}. \tag{6a}$$

$$\eta_{cycle} = W_{cycle}/\dot{Q}_{cycle}. \tag{6b}$$

It should be noted, however, that the actual net power of the DEMO plant and the related net plant electrical efficiency will be much lower than the respective values resulting from Eqs. (3) and (6b), since in the present analysis we have not taken into account power consumption of the DEMO auxiliary systems, e.g. those required for heating and current drive in the plasma, cryogenic plant, vacuum pumps, etc.

3. Results

We obtained the convergent GC model (in the "Design" mode) for the whole considered PCS cycle at the nominal conditions. The main operating parameters of this model are compiled in Table 1, whereas the respective T-s diagram is shown in Fig. 2a. Then we obtained the convergent GC models (in the "off design" mode) for several cases with the reduced heating power, namely with $\dot{Q}_{DIV} = 0$MW and $\dot{Q}_B$ (duty of the heat exchanger HX1) consecutively reduced to 80, 75, 70, 65, 60, 55 and 50% of its nominal value. The values of the operating parameters for the latter case are listed in Fig. 1. It can be noticed, that at the reduced heating power

Table 1
Parameters of the selected streams at the nominal operating conditions ($\dot{Q}_B$ = 2129MW, $\dot{Q}_{DIV}$ = 148MW).

Stream	$\dot{m}$ (kg/s)	T (°C)	p (kPa)	quality, x
S_0	1 218	243	6 405	0
S_1	1 218	280	6 400	1
S_3	1 122	280	6 400	1
S_5	96	247	3 800	0.9384
S_6	74	215	2 100	0.8925
S_4	952	180	1 000	0.8528
S_19	753	180	1 000	1
S_20	753	261	1 000	1
S_21	85	114	162	0.9732
S_22	668	32	4.8	0.8398
S_37	753	32	4.8	0.7612
S_44	753	32	4.8	0
S_36	753	90	317	0
S_35	933	107	600	0
S_28a	933	144	600	0
S_25	952	154	600	0
S_15	952	175	6 405	0
S_9	952	211	6 405	0
S_12	1 218	212	6 405	0

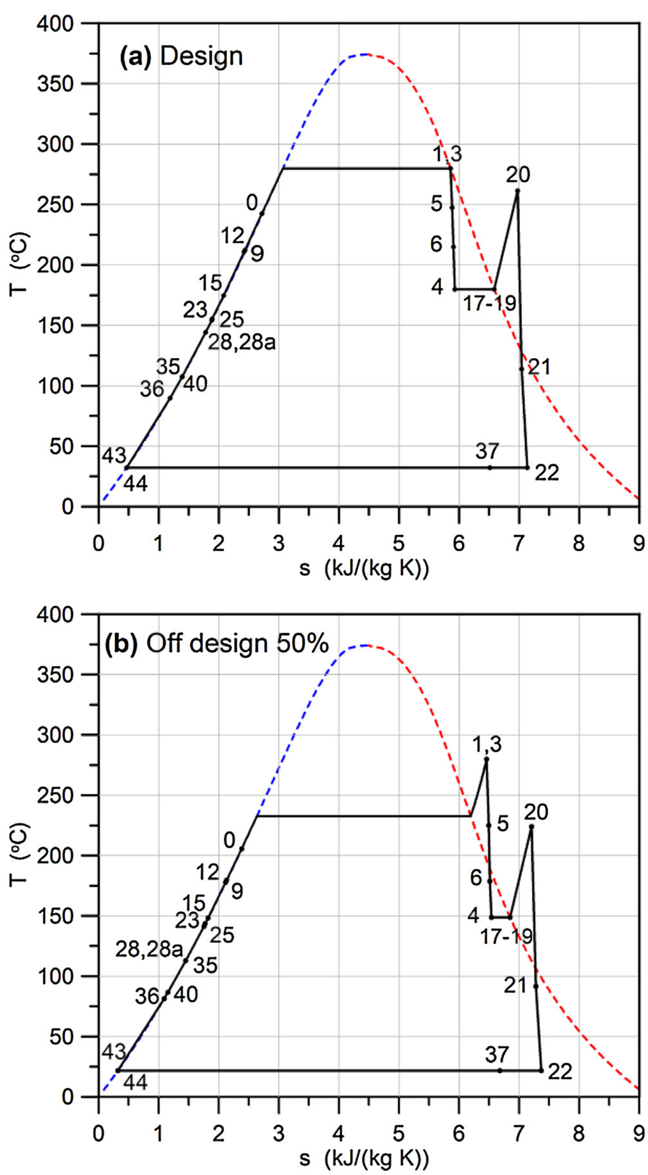

Fig. 2. T-s diagram for the considered cycle (a) at the nominal operating conditions, (b) for operation during the dwell period ($\dot{Q}_B$ = 1065MW, $\dot{Q}_{DIV}$ = 0MW).

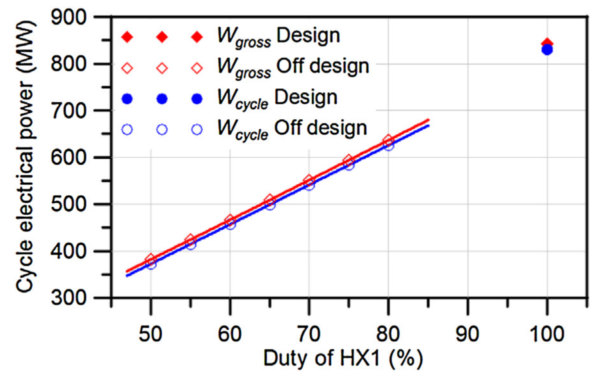

Fig. 3. Power of the considered cycle at the nominal operating conditions and at the reduced heating power.

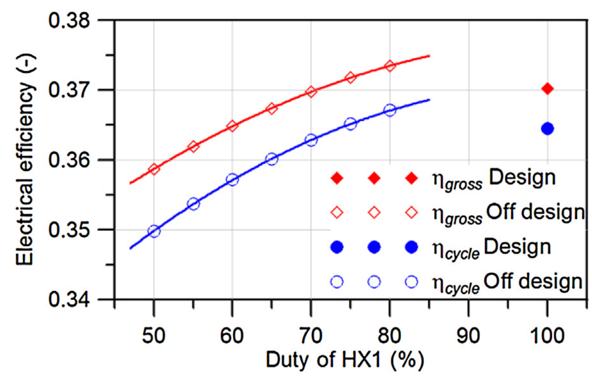

Fig. 4. Electrical efficiency of the cycle at the nominal operating conditions and at the reduced heating power.

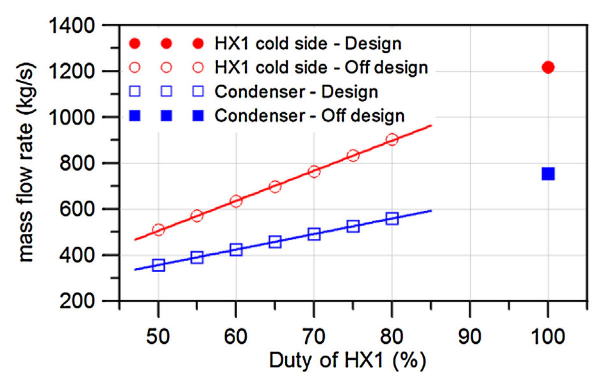

Fig. 5. Mass flow rate of water heated in the HX1 and water at the condenser main exit, at the nominal conditions and at the reduced power.

temperature at the inlet of the HP turbine (stream S_3 in Fig. 1) is the same as in the nominal operating conditions. Steam quality in turbines at the reduced heating power slightly increases, which is beneficial for the turbines internal efficiencies. At part load operation turbines' power is reduced by reduction of the mass flow rate and pressure in the HX1. Comparison of Fig. 3a and b, as well as Fig. 1 and Table 1, reveals that at the reduced power steam is expanded in turbines at lower pressure and higher x. At the reduced power, initial part of the steam expansion in the HP turbine takes place in the superheated region.

The power of the considered cycle, its electrical efficiency and the mass flow rate of water in the main circuit (streams S_0 and S_44 in Fig. 1), at the nominal operating conditions (plasma burn) and at the reduced heating power (dwell phase) is presented in Figs. 3–5. It is seen, that the gross electrical power of the cycle varies in the range 843-382 MW, whereas the gross electrical efficiency – in the range 37.3–35.9%. The pump work, which varies in the range 13–9.5 MW, does not affect significantly the electrical output. Although utilizing heat from the divertor source increases the cycle power, but slightly reduces its electrical efficiency. Reduction of the heating power provided to the cycle is accompanied by the linear reduction of the water/steam mass flow rate in the main circuit.

4. Summary and conclusions

The detailed convergent GC model of the steam/water PCS cycle for the DEMO power plant (option WCLL with the ESS) was created and its operation at the nominal conditions and at the reduced heating power was studied. It was demonstrated, that during the dwell period the amount of heat provided from the ESS to the cycle can be safely reduced down to 50% of its nominal value. This is an important information for the designers of the ESS which should help in its proper sizing.

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