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Design and Analysis of the Secondary Circuit of the DEMO Fusion Power Plant for the HCPB BB Option without the Energy Storage System and with the Auxiliary Boiler

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The EU DEMO (European DEMOnstration Fusion Power Plant) is being designed to produce fusion electricity at a level of several hundred MW, by about 2060. The Primary Heat Transfer System (PHTS) transfers heat from the fusion reactor heat sources, namely: Breeding Blanket (BB), Divertor (DIV) and Vacuum Vessel (VV), to the Power Conversion System (PCS) responsible for the generation of electricity. Four cooling concepts for the EU DEMO BB and the related PHTS are considered, including the Helium Cooled Pebble Bed (HCPB) BB. In some variants the Intermediate Heat Transfer System (IHTS) with the Energy Storage System (ESS) filled with molten salt has been added between the PHTS and PCS, in order to mitigate transient effects resulting from the pulsed plasma operation. However, such a solution introduces complexity in the plant design, so in parallel other options with a direct coupling of the PHTS with the PCS (without the IHTS/ESS) are also being investigated. The primary solution is to use an auxiliary boiler (AUXB) powered by a natural gas burner for steam production: partly during the pulse time operation and fully during the dwell time operation of EU DEMO. In the present work the detailed convergent GateCycle model of the steam/water PCS, for the option HCPB BB without the IHTS/ESS and with the AUXB, was created and its operation at the nominal conditions (plasma pulse) and at thermal power reduced down to ~50% of the nominal value (dwell period) was simulated. It was demonstrated, that the proposed PCS circuit can operate in a stable manner with the gross electrical power of 1120 MW and 547 MW during the pulse and dwell phase, respectively. The gross electrical efficiency of the proposed PCS circuit is of about 42% during the both phases. However, the observed problems, namely: huge size of the AUXB and relatively large pressure pulsations $\Delta p = |p_{pulse} - p_{dwell}|$, require attention and further studies on feasibility of the proposed concept.

GOALS

- Development of the GateCycle model of the steam/water PCS circuit for the EU DEMO fusion power plant (option: HCPB BB without the IHTS/ESS with the auxiliary boiler [1]).
- Study possibility of stable operation of considered PCS circuit at the nominal conditions (plasma pulse) and at the reduced thermal power (dwell phase).

SUMMARY and CONCLUSIONS

- Convergent GateCycle model of the PCS configuration, for the option HCPB BB without IHTS/ESS with AUXB, of the EU DEMO plant was developed and its operation during the plasma burn and during the dwell phase (at power reduced down to 50%) was simulated.
- The model provided preliminary sizing of the circuit components, which could help in their cost assessment.
- The proposed PCS circuit can operate in a stable manner with the gross electrical power of 1120 MW and 547 MW during the pulse and dwell phase, respectively.
- Temperature fluctuations $|T_{pulse} - T_{dwell}|$ as well as pressure pulsations $|p_{pulse} - p_{dwell}|$ in most of the circuit components seem moderate, nevertheless further studies on fatigue or burst failure risks caused by frequent transients are necessary to justify the feasibility of the proposed concept. There are also some doubts on the high amount of fuel needed to operate the postulated AUXB, as well as on its large size.

BASIC DEFINITIONS

- Shaft power of the *i*-th turbine (i = 1,2):

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

where n_{se} = 4 or 3 is the number of steam extractions, η_t =0.998 [2] is the turbine mechanical efficiency.

- Generator output:

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

where η_{gen} = 0.98 [2] is the generator efficiency.

- Electrical power of the cycle:

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

where W_{pump} is the pump power, calculated as:

$$W_{pump} = \dot{m}_{pump}(h_{out} - h_{in}) / \eta_{pump}$$

and η_{pump} = 0.998 [1] is the pump motor efficiency.

- Rate of heat supplied to the cycle:

$$Q_{cycle} = Q_{BB,cy} + Q_{DIV\ CAS,cy} + Q_{DIV\ PFU,cy} + Q_{VV,cy} + Q_{Boiler}$$

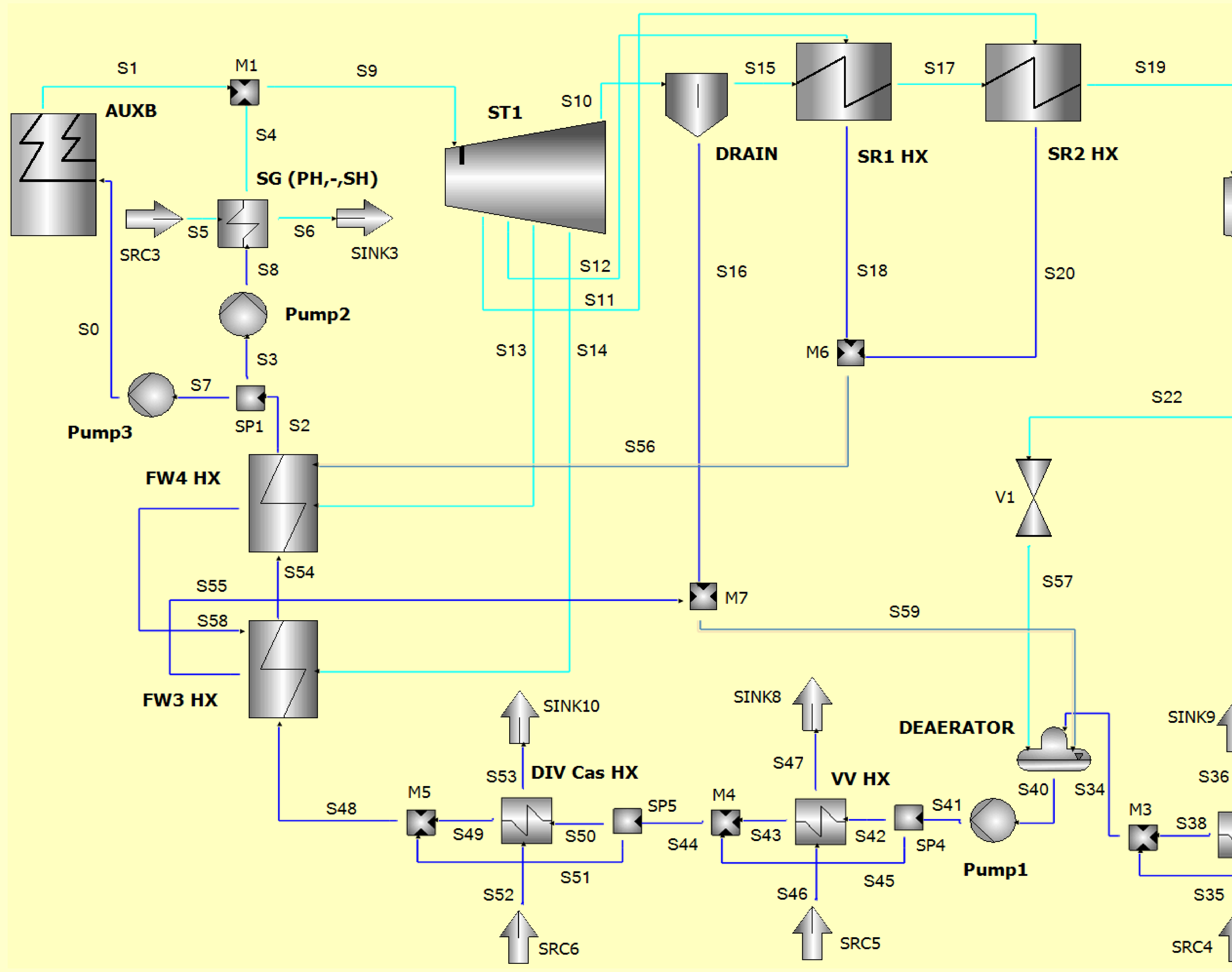
- Rate of heat released from the reactor heat sources:

$$Q_{Reactor} = Q_{BB} + Q_{DIV\ CAS} + Q_{DIV\ PFU} + Q_{VV}$$

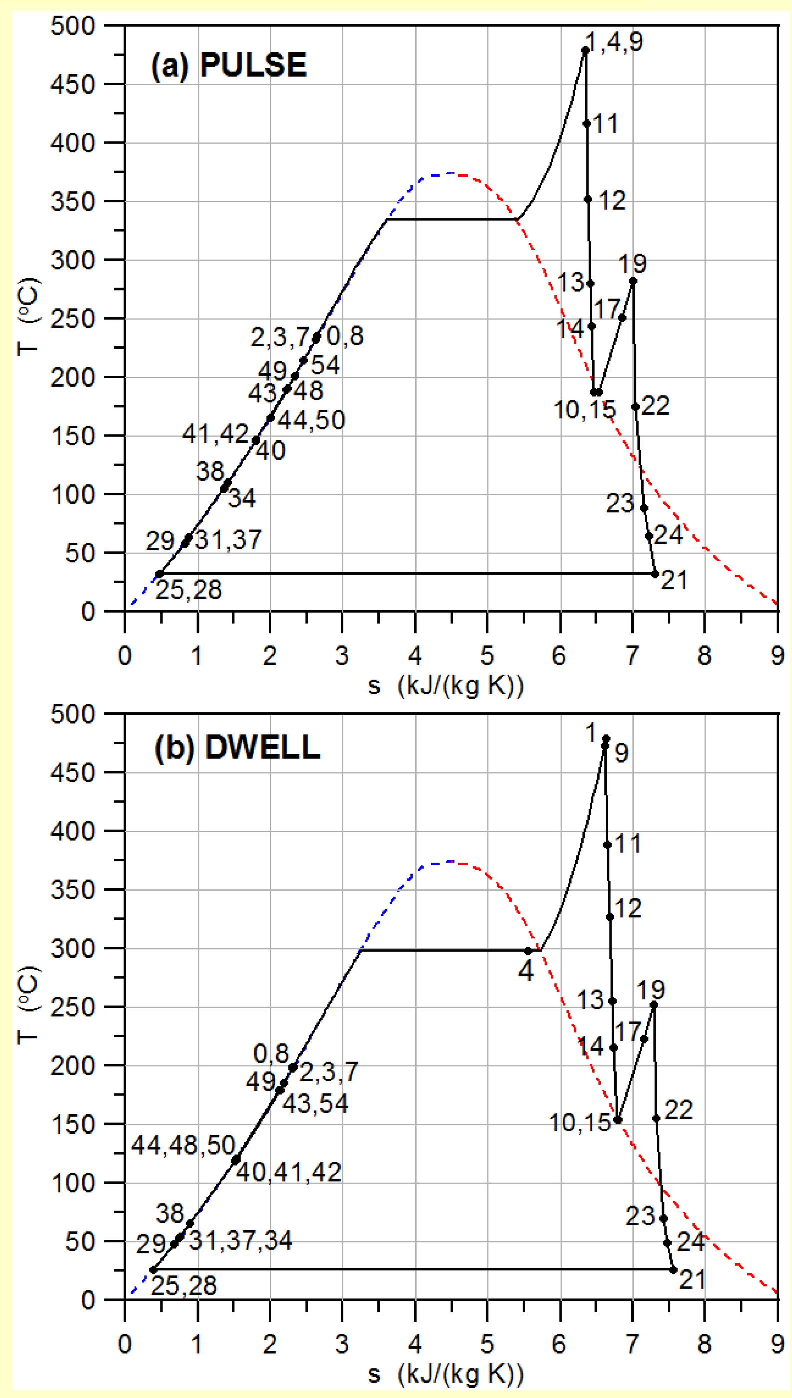
- Overall electrical efficiency of the cycle:

$$\eta_{gross} = W_{gross} / (Q_{Reactor} + Q_{Boiler}) \qquad \eta_{cycle} = W_{cycle} / Q_{cycle}$$

RESULTS



Stream	From	To	PULSE				DWELL			
			ṁ (kg/s)	p (MPa)	T (°C)	quality, x	ṁ (kg/s)	p (MPa)	T (°C)	quality, x
S9	M1	ST1	1061.7	13.626	480.0	1	532.5	8.379	473.7	1
S11	ST1	SR2 HX	34.0	9.100	417.3	1	12.4	4.632	388.7	1
S12	ST1	SR1 HX	71.9	5.711	352.1	1	30.1	2.896	327.2	1
S13	ST1	FW4 HX	34.1	3.202	280.7	1	18.1	1.565	255.5	1
S14	ST1	FW3 HX	52.4	2.293	243.5	1	61.8	1.070	215.5	1
S10	ST1	DRAIN	869.4	1.188	187.5	0.986	410.2	0.536	154.5	0.995
S15	DRAIN	SR1 HX	857.2	1.188	187.5	1	408.1	0.536	154.5	1
S17	SR1 HX	SR2 HX	857.2	1.156	250.7	1	408.1	0.519	222.8	1
S19	SR2 HX	ST2	857.2	1.125	282.2	1	408.1	0.502	252.0	1
S22	ST2	V1	34.6	0.426	174.9	1	29.9	0.193	155.0	1
S23	ST2	FW2 HX	8.3	0.067	88.7	0.946	4.1	0.030	69.4	0.951
S24	ST2	FW1 HX	41.6	0.025	64.7	0.911	14.8	0.012	48.9	0.917
S21	ST2	COND	772.7	0.005	32.5	0.861	359.3	0.003	26.0	0.879
S25	COND	FW pump	822.5	0.005	32.5	0	378.2	0.003	26.0	0
S28	FW pump	FW1 HX	822.5	0.457	32.6	0	378.2	0.198	26.0	0
S29	FW1 HX	FW2 HX	822.5	0.452	58.7	0	378.2	0.195	47.4	0
S31	FW2 HX	SP3	822.5	0.447	64.0	0	378.2	0.192	53.4	0
S37	SP3	DIV PFU	744.0	0.447	64.0	0	28.5	0.192	53.4	0
S38	DIV PFU	M3	744.0	0.442	109.9	0	28.5	0.192	65.3	0
S34	M3	Deaerator	822.5	0.442	105.6	0	378.2	0.192	54.2	0
S40	Deaerator	Pump 1	1061.7	0.425	145.8	0	532.5	0.191	118.8	0
S41	Pump 1	SP4	1061.7	5.778	147.0	0	532.5	5.715	120.0	0
S42	SP4	VV HX	466.6	5.778	147.0	0	3.9	5.715	120.0	0
S43	VV HX	M4	466.6	5.773	189.5	0	3.9	5.715	179.7	0
S44	M4	SP5	1061.7	5.773	165.9	0	532.5	5.715	120.4	0
S50	SP5	DIV Cas	740.5	5.773	165.9	0	3.8	5.715	120.4	0
S49	DIV2 Cas	M5	740.5	5.721	201.2	0	3.8	5.715	185.4	0
S48	M5	FW3 HX	1061.7	5.721	**190.7**	0	532.5	5.715	**120.9**	0
S14	PCS ST1	FW3 HX	52.4	2.293	243.5	1	61.8	1.070	215.5	1
S54	FW3 HX	FW4 HX	1061.7	5.715	214.4	0	532.5	5.714	179.2	0
S2	FW4 HX	SP1	1061.7	5.710	232.6	0	532.5	5.712	198.5	0
S3	SP1	Pump 2	961.3	5.710	232.6	0	12.2	5.712	198.5	0
S8	Pump 2	SG (PH,-,SH)	961.3	13.695	235.5	0	12.2	8.400	199.4	0
S4	SG (PH,-,SH)	M1	961.3	13.627	480.0	1	12.2	8.400	298.4	0.930
S7	SP1	Pump 3	100.4	5.710	232.6	0	520.3	5.712	198.5	0
S0	Pump 3	AUXB	100.4	13.696	234.7	0	520.3	8.900	199.2	0
S1	AUXB	M1	100.4	13.626	480.0	1	520.3	8.379	480.0	1



in MW	Pulse	Dwell
$Q_{BB,cy}$	2167.27	22.01
$Q_{DIV\ CAS,\ cy}$	115.34	1.07
$Q_{DIV\ PFU,\ cy}$	143.73	1.42
$Q_{VV,\ cy}$	85.99	0.86
$Q_{Boiler,\ cy}$	226.77	1297.13
Q_{cycle}	2739.32	1322.63
$Q_{Reactor}$	2438.9	24.51

in MW	Pulse	Dwell
W_{gross}	1120.5	546.6
W_{cycle}	1095.1	535.9

in %	Pulse	Dwell
η_{gross}	42.0	41.4
η_{cycle}	40.0	40.5

in MW	Pulse	Dwell
W_{t1}	500.7	286.5
W_{t2}	642.6	271.3

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EUROfusion

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