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Conceptual Designs of PHTS, ESS and PCS Components for DEMO BoP with Helium Cooled BB Concept

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The present state of EU DEMO Balance of Plant (BoP) is described in this paper. Starting with 6 outboard and 3 inboard cooling loops, the thermal energy of the helium is transferred by an intermediate HX to the solar salt, which transports it out of the tokamak building to the energy storage system, which is actually an industrial 2-tanks design. Heat is transferred from solar salt to the feedwater in the steam generator where it boils and becomes superheated before entering the steam turbine. The steam turbine design follows state-of-the-art concept, but it is not finally optimized, since further DEMO BoP design changes still cannot be excluded. The other 3 usable heat sources (DIV-PFU, DIV-Cas and VV) are used to heat-up the feedwater on the return line to the steam generator, thus contributing to the efficient utilization of heat produced during DEMO operation. Taking into account pulse/dwell times of 2.0/0.5 h, DEMO can operate permanently under ~80% power thus allowing flexible and continuous plant operation. EBSILON® results are presented for steady-state conditions including both pulsed and dwell time periods.

Keywords: DEMO, Balance of Plant, Energy Storage System, Helium Cooled Breeding Blanket, pulsed operation

1. Introduction

The KIT fusion work is well integrated within the German Helmholtz Programme Nuclear Fusion and within the European Fusion Programme (EUROfusion). Within EUROfusion, KIT is contributing to 18 out of 36 Work Packages, mostly within the Power Plant Physics and Technology (PPPT) section, in close collaboration with many other EUROfusion members. In the framework of the EUROfusion PPPT, the Working Package Breeding Blanket (WPBB) aims at investigating 4 different Breeding Blanket (BB) concepts for a EU Demonstration Fusion Reactor (DEMO) [1]. One of these concepts is the Helium Cooled Pebble Bed (HCPB) BB, which is based on the use of pebbles of lithiated ternary compounds and Be or beryllides as tritium breeder and multiplier materials respectively, EUROFER97 as structural steel and He as coolant. KIT experts belonging to the EUROfusion PPPT Work Package Balance of Plant (WPBOP) are working on the design of DEMO BoP, for the HCPB BB option.

The task of Balance of Plant (BoP) for DEMO is to utilize heat from different internal sources, such as Breeding Blanket (BB), Divertor (DIV) and Vacuum Vessel (VV) and to convert it into electricity in an optimum way so to fulfill the objective of a DEMO power plant to be commercially feasible supplying electricity to the future energy mix.

As the plasma current in the tokamak is induced by an increasing current in the poloidal coils, the induction, and consequently the pulse will cease once the current reaches its maximum value. This means that tokamak has to operate in pulsed mode and therefore the thermal energy generated by the fusion reactions are followed by a dwell time when only the decay heat of the fusion and active products is produced (~1-3 % nominal power). This step-wise thermal power profile has a strong influence in the design of DEMO BoP. All systems and components in PHTS are subjected to unavoidable power cycles; however, efforts are put in the design of the BoP to avoid power cycle effects on all the BoP components.

The main idea to solve the power cycles was the introduction of the Intermediate Heat Transfer System (IHTS) with solar salt as fluid between the BB Primary Heat Transfer System (PHTS) and the Power Conversion System (PCS), where solar salt can store thermal energy during pulse operation and release it during dwell time period. Moreover, a thermal Energy Storage System (ESS) would ensure flexibility to DEMO while supplying electricity to the grid. Without ESS DEMO could only operate as base load provider during pulsed operation time. As for the power demand of mechanical components (pumps, compressors, mechanical valves, etc.), ESS also provides thermal power that can be converted to electricity and used for in-house needs.

This paper presents the process followed to optimize the BoP design for the HCPB BB option, particularly the IHTS and PCS systems, providing a reliable conceptual design based on the technology readiness existing in other energy systems, such as Concentrated Solar Power (CSP) plants, LWR fission power plants, etc.

2. DEMO BoP Description

DEMO BoP for HCPB BB option consists of a chain of systems (refer to Fig.1), including the BB PHTS, the IHTS with a thermal ESS to cope with dwell times, and the PCS itself [2].

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The present state of DEMO BoP for HCPB BB option is presented schematically in Fig. 1. Starting with 6 outer and 3 inner blankets loops the energy of the helium is transferred by an intermediate HX to the solar salt, which transports it out of the tokamak building to the ESS, which is an industrial 2-tanks design. Heat is transferred from solar salt to the steam generator (SG) that boils and superheats the feedwater and delivers steam to the steam turbine. The steam turbine design follows state-of-the-art concept, but it is not finally optimized, since further DEMO BoP design changes still cannot be excluded. The other usable heat sources (DIV-PFU, DIV-Cas and VV) are used to heat-up the feedwater on the return line to the steam generator. Taking into account pulse/dwell times of 2.0/0.5 h, DEMO can operate permanently under ~80% power thus allowing flexible and continuous plant operation without interfering with plasma operation. Due to the live steam extraction for feedwater preheating from high pressure and low pressure turbine stages, the efficiency of the PCS is increased, thus reducing the burden to the ESS also during the dwell time.

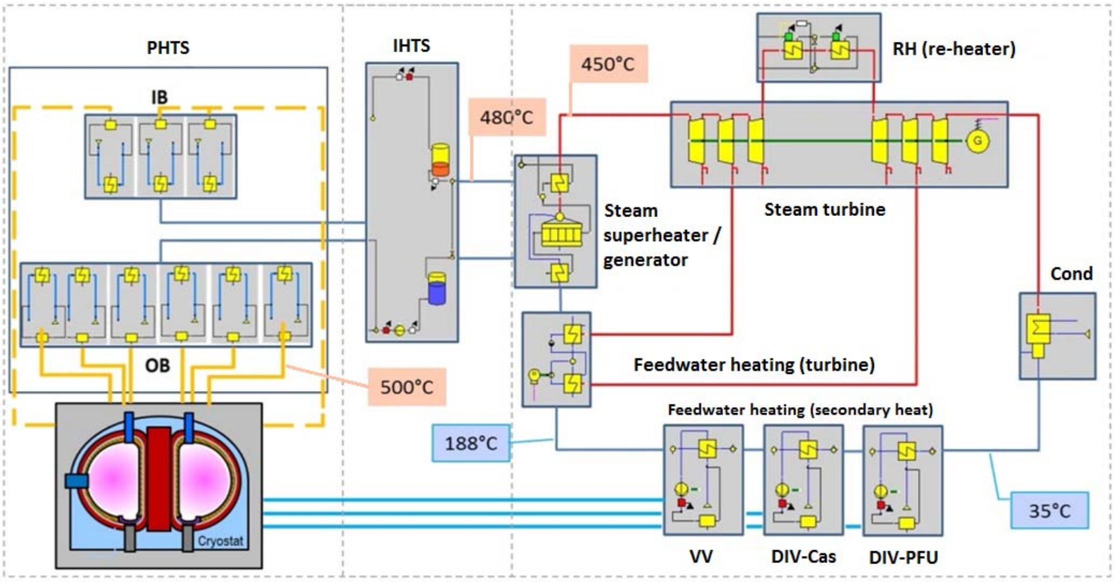

Fig. 1. Schematic representation of the HCPB BoP design.

2.1 PHTSs

Four independent PHTSs are present in DEMO which receive heat from BB, DIV-Cas, DIV-PFU and VV heat sources. Main parameters of the DEMO PHTSs are shown in Table 1.

BB heat source has 9 independent heat transfer loops in total: 3 heat transfer loops for the inboard blanket (IB) sectors and 6 heat transfer loops for the outboard blanket (OB) sectors. Each of the 9 BB heat transfer loops has its own heat exchanger (HX) [3] and 2x50% blowers to cope with partial Loss Of Flow Accident (LOFA) in case of one blower failure thus ensuring the possibility to remove the decay heat from the affected loop (the final number of helium blowers is based on the available capacity of helium blowers on the market). Each IB heat transfer loop transfers ~234.9 MW and each OB heat transfer loop transfers ~303 MW heat, correspondingly to the solar salt in a Helium/solar salt HX.

During dwell time helium flow rate is reduced as thermal energy deposited is drastically reduced down to the decay heat level. Consequently, pumping power in the helium compressors is expected to be significantly lower* than nominal (~ 177 MW during pulse time).

Table 1. Main parameters of the DEMO PHTSs.

	BB	DIV-Cas	DIV-PFU	VV
Coolant	Helium	Water	Water	Water
Thermal Power pulsed/dwell (MW)	2389.1/21.4	115.2/1.07	136/1.421	86/1.0
Mass flow rate pulsed/dwell (kg/s)	2303.8/41.3	861.1/861.1	3260.6/3260.6	1928.9/1928.9
Inlet temperature pulsed/dwell (°C)	500/400	210/195	140/135	200/195
Outlet temperature pulsed/dwell (°C)	300/300	180/194.7	130/134.7	190/194.9
Operational pressure (bar)	80	35	50	31.5

The other 3 heat sources (DIV-PFU, DIV-Cas and VV) are used to heat-up the feedwater on the return line to the steam generator, which produces steam for the steam turbine. Each of these heat sources has its own HX

** The magnitude of the blowers power during dwell time will depend on the possible and effective regulation of the pumping group.*

and a water pump. In order to ensure that the correct amount of heat is being transferred to the PCS and that the returning water to each of the 3 heat sources (DIV-PFU, DIV-Cas and VV) has its design parameters, feedwater flow around the 3 corresponding HXs is being split into the main flow and the by-pass flow [4].

2.2 IHTS/ESS

Solar salt tanks in the IHTS (ESS) are used to accumulate the required amount of heat in the form of sensible heat of the solar salt, which replaces the BB heat source during the dwell time, when DEMO is producing almost no heat (see section 1). This is important to ensure the continuous operation of the power train composed of steam turbine and generator, thus producing electricity and keeping the whole PCS operational all the time. Main parameters of the DEMO ESS are shown in Table 2.

ESS of the DEMO is an industrial 2-tanks design commonly used in CSP plants, however investigations are on-going in order to replace the 2-tanks system with more efficient 1-tank thermocline system. With a duty cycle (pulse/dwell) time of 2.0/0.5 h, thanks to ESS, DEMO can operate permanently under ~80% power thus allowing flexible and continuous plant operation. Estimated solar salt mass required for such an operation is ~11300 tons for 30 min dwell time case. In case dwell time could be decreased, correspondingly the required solar salt mass for such ~80% continuous plant operation would reduce as well. During dwell time solar salt of the ESS could also replace the power missing in the PCS from DIV-PFU, DIV-Cas and VV heat sources.

Table 2. Main parameters of the DEMO ESS.

Coolant	Solar Salt
Thermal Power (MW)	~1990
Mass flow rate (kg/s)	~6209
Hot tank temperature (°C)	480
Cold tank temperature (°C)	268
Operational pressure (bar)	1.0

Table 3. Main parameters of the DEMO PCS.

Coolant	Water/Steam
Gross Power pulsed/dwell (MW)	~808/~730
Net Power pulsed/dwell (MW)	~659/~713
Inlet HP turbine temperature (°C)	~445
Outlet HP turbine temperature pulsed/dwell (°C)	~177/~169
Inlet LP turbine temperature pulsed/dwell (°C)	~258/~253
Outlet LP turbine temperature pulsed/dwell (°C)	~33/~30
Mass flow rate pulsed/dwell (kg/s)	~791/~786
Cold heat sink temperature (°C)	18
Live steam pressure pulsed/dwell (bar)	~45.9/~44.5

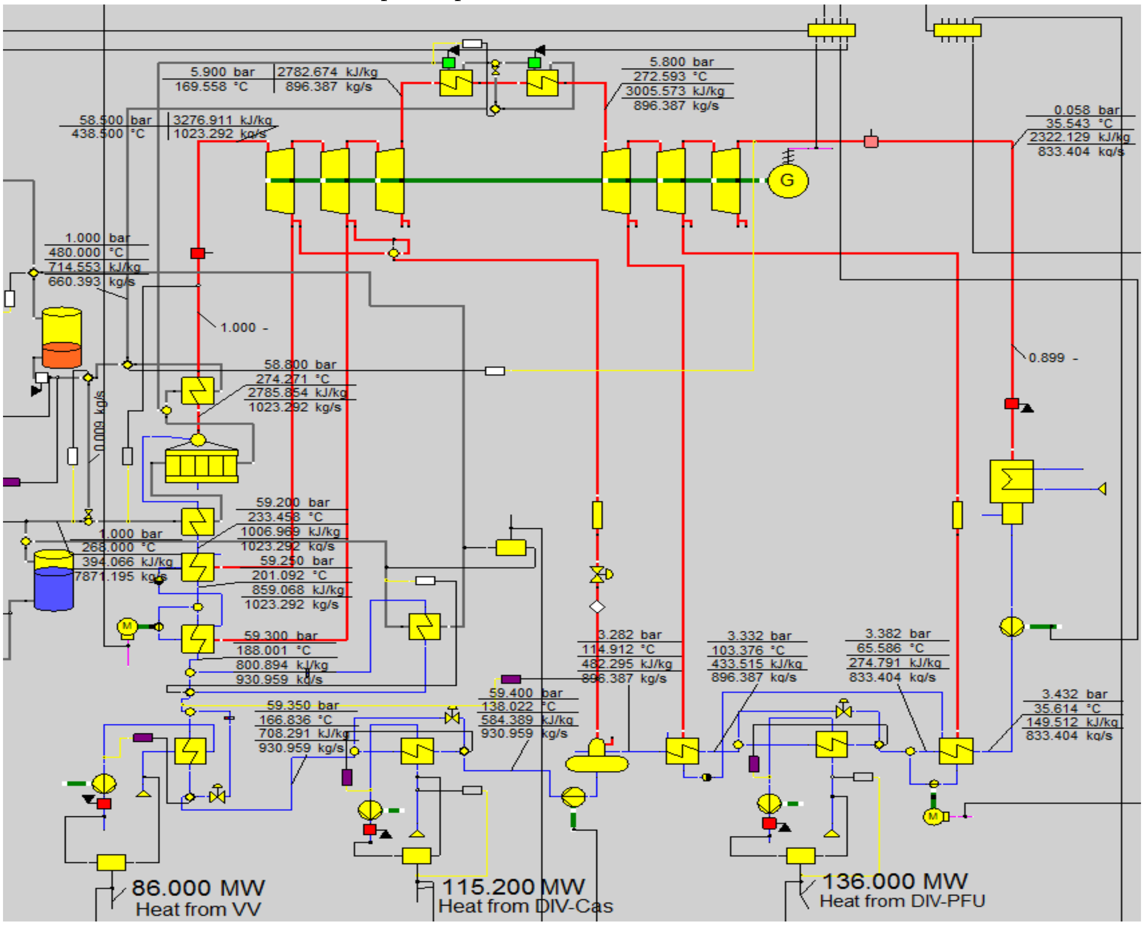

Fig. 2. DEMO PCS model in EBSILON®.

2.3 PCS

PCS of DEMO is a state-of-the-art water-steam Rankine cycle, with the efficiency currently of ~36%. Main parameters of the DEMO PCS are shown in Table 3. Critical components requiring stable operational conditions are: turbine (stable steam temperature and flowrate) and deaerator (stable operating pressure and temperature). Reheating of the steam between the high pressure and the low pressure turbine stages is realized using hot solar salt from the ESS which is returned to the cold tank at 268°C after passing through the SG. Design provision on the feedwater inlet temperature to all the HXs supplied by hot solar salt has to be taken in order to avoid solar salt freezing (~220°C). Solar salt temperatures in the hot and cold tank are kept constant using the corresponding solar salt flow regulators. The currently realized scheme of the DEMO PCS is presented in Fig. 2, while the T-s diagram of the simulated PCS Rankine cycle is presented in Fig. 3. Steam extractions from the high pressure and low pressure steam turbine stages used for feedwater preheating are not in a final optimized state. In order to fix this issue, KIT started an industrial cooperation to get data for a state-of-the-art steam turbine, including actual parameters of the steam extractions, with the aim to reach higher efficiency of the PCS Rankine cycle.

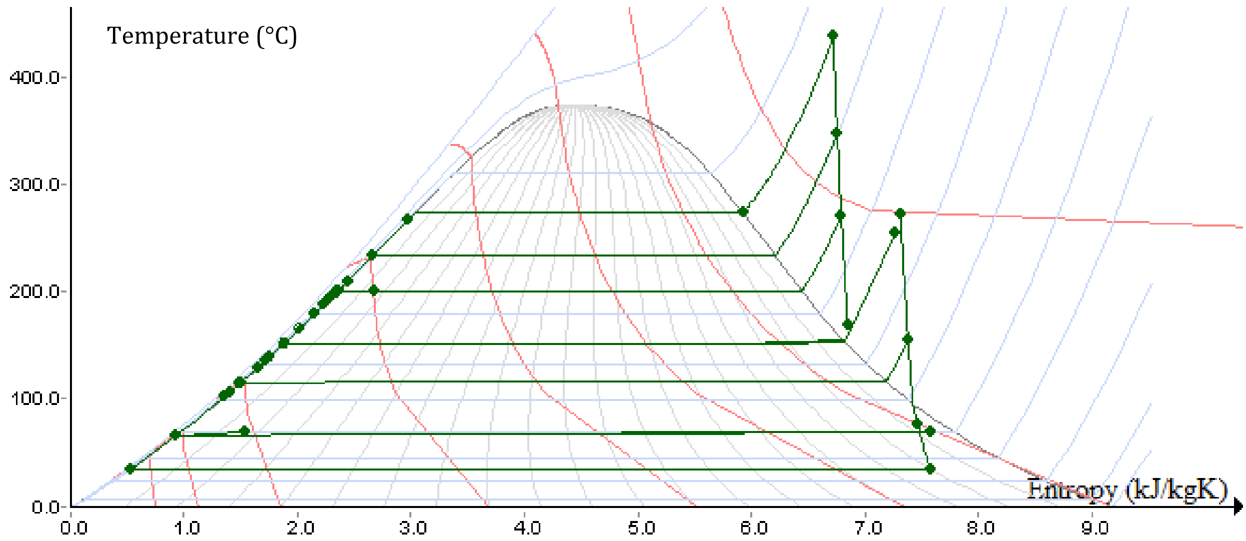

Fig. 3. DEMO PCS Rankine cycle T-s diagram.

2.4 Simulation of DEMO BoP

As part of the overall DEMO BoP design, KIT developed a plant model using the industrial code EBSILON® which, providing a comprehensive map of all thermal-hydraulic parameters in the relevant points of the plant, helps to quickly get information on the consequences of all on-going DEMO design optimizations.

EBSILON® is a software package that simulates thermodynamic cycle processes and is used for engineering, designing, and optimizing of different kinds of power plants. EBSILON® supports the engineering processes from feasibility studies all through to the detailed dimensioning of a power plant [5]. EBSILON® can be run either in a static or a quasi-static mode, thus real dynamic simulations of DEMO BoP are presently not possible.

Results of quasi-static simulations show that the current configuration of DEMO BoP can operate permanently under ~80% power thus allowing continuous plant operation and flexibility in the range of turbine power scale of ±20%. A further optimization currently is not worthwhile, since during the on-going development of DEMO, significant modifications still have to be expected. During the final optimization of the DEMO PCS model, the usage of the available heat sources in a more efficient way is foreseen, thus enabling a more smooth operation of the steam cycle, especially the deaerator.

3. Conclusions

A short overview of the current DEMO BoP design, for HCPB BB option, being developed at KIT is presented. The present DEMO BoP includes a BB PHTS consisting of 9 blankets loops, where energy of the helium is transferred via IHTS to the ESS, which is an industrial 2-tanks design common for the CSP plants. Heat is transferred from solar salt to the steam generator that boils and superheats the feedwater and delivers steam to the steam turbine. The steam turbine design follows state-of-the-art concept, but it is not finally optimized. Taking into account pulse/dwell times of 2.0/0.5 h, DEMO can operate permanently under ~80% power thus allowing flexible and continuous plant operation. In summary, all presently developed mechanisms of fossil fuel plants to cope with fluctuating grid demands are available, plus the heat stored in the ESS. Using all these techniques, a future FPP seems suited to replace fossil fuel power plants also for grid stabilization.

4. On-going activities in 2017

Activities on-going in 2017 include the following actions: 1) Adaptation of DEMO BoP to include real steam turbine configuration; 2) Stabilization of deaerator operating conditions (operating pressure and temperature); 3) Stabilization of feedwater temperature at steam generator entrance; 4) Maximal reduction of the impact of DEMO pulsating mode of operation on all DEMO BoP components, first of all on the steam turbine and the electricity generator; 5) Changing IHTS fluid from solar salt to HITEC salt, which is beneficial, while HITEC salt has a lower freezing point than the solar salt, thus consequently provide the designers greater flexibility while designing the PCS; 6) Tuning of the Rankine cycle (PCS) design according to the evolution of the BB power and dwell time; 7) Sizing and selection of the components for DEMO BOP configuration relying to the maximum extent on proven industrial technology; 8) Estimation of space requirements and weight of different components. Another important activity foreseen for 2017 is the feasibility study and proposal for realization of DEMO BoP configuration without the IHTS/ESS.

Acknowledgments

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