Elsevier Editorial System(tm) for Fusion Engineering and Design
Manuscript Draft

Manuscript Number: FUSENGDES-D-19-00209R1

Title: Proposal of optimized power cycles for the DEMO power plant (EUROfusion)

Article Type: Full Length Article

Keywords: Keywords: DEMO; EUROFusion; Rankine cycles; Energy Storage System; Cycle optimization.

Corresponding Author: Dr. Antonio Rovira, Doctor

Corresponding Author's Institution: UNED

First Author: Antonio Rovira, Doctor

Order of Authors: Antonio Rovira, Doctor; Consuelo Sánchez; María José Montes; Marta Muñoz

Abstract: The objective of this paper is the proposal of two configurations of Rankine cycles different from the standard solution considered for the DEMO 2017 design. The configurations are aimed to maintain as constant as possible the operation at the pulse and dwell modes with minimal fluctuations in the turbine and heat exchangers parameters, in order to maximize the reliability of these components. Each configuration, as well as the reference one, have been simulated both at pulse and dwell operation modes.
Compared to the reference design, the proposed configurations are much steadier and mass flow rates in the steam generator and preheaters are constant. In summary, it is possible to ensure a completely steady operation of the whole steam cycle, including all the heat exchangers, without differences between the pulse and dwell modes using two secondary storage tanks additional to the two original molten salt ones.

Research Data Related to this Submission

Title: Data for: Proposal of optimized power cycles for the DEMO power plant (EUROfusion)
Repository: Mendeley Data
https://data.mendeley.com/datasets/tfvdsngwgb/draft?a=ad908b29-5bdd-41adbf6e-d1c9c56c131e

Highlights

- Proposal of two PCS different from the solution considered for the DEMO 2017.
- Configurations aimed to maintain constant the operation at the pulse and dwell.
- Secondary energy storage system for the cooling of divertor and vacuum vessel.
- Configurations are simulated both at pulse and dwell operation modes.
- They allow a completely steady operation of the power conversion system.

*Manuscript (clean version)
Click here to view linked References

Proposal of optimized power cycles for the DEMO power plant (EUROfusion)

Antonio Rovira[1,*], Consuelo Sánchez[1], María José Montes[1], Marta Muñoz[1].

[1]Universidad Nacional de Educación a Distancia (UNED), Address: Calle Juan del Rosal, 12, 28040 Madrid

[*]Tel.: +34 91 398 82 24

e-mail addresses: rovira@ind.uned.es (A Rovira); csanchez@ind.uned.es (C Sánchez); mjmontes@ind.uned.es (MJ Montes); mmunoz@ind.uned.es (M Muñoz).

Abstract

The objective of this paper is the proposal of two configurations of Rankine cycles different from the standard solution considered for the DEMO 2017 design. The configurations are aimed to maintain as constant as possible the operation at the pulse and dwell modes with minimal fluctuations in the turbine and heat exchangers parameters, in order to maximize the reliability of these components.

Each configuration, as well as the reference one, have been simulated both at pulse and dwell operation modes.

Compared to the reference design, the proposed configurations are much steadier and mass flow rates in the steam generator and preheaters are constant. In summary, it is possible to ensure a completely steady operation of the whole steam cycle, including all the heat exchangers, without differences between the pulse and dwell modes using two secondary storage tanks additional to the two original molten salt ones.

Keywords: DEMO; EUROFusion; Rankine cycles; Energy Storage System; Cycle optimization.

1. Introduction

DEMO is a research project focused on the development of a demonstration fusion reactor prototype that shall deliver to the electrical grid several hundred MW. It has the objective of being an intermediate step between ITER and a commercial fusion reactor [1]. Its roadmap considers the evaluation of multiple design options and parallel investigations for systems and technologies with different technical risk or degree of novelty, for example for Breeding Blanket (BB) technology and coolants, power exhaust solutions, power conversion systems, etc. [2]

There are four options considered for cooling the reactor (Primary Heat Transfer System, PHTS) [3]. One of the most promising is the use of Helium Cooled Pebble Bed (HCPB) BB [1]. According to the current EU DEMO baseline design [4], the DEMO reactor must work in two modes of operation: A pulse mode in which the plasma state is induced thanks to an increasing current in the solenoid; and a dwell mode that takes place when the exciting current reaches its maximum value. The fusion reactions take place during the pulse mode, which produce significant thermal power. During the dwell time only the decay heat of the fusion and active products is produced (∼1–3% nominal power). Therefore, the reactor generates thermal energy in pulses of about 120 min that are interrupted by dwell periods of about 10 min [4].

The breeding blanket is the most important device in terms of thermal energy generation (about 85 %) [1], because it is where the nuclear reaction takes place (not the fusion ones) and the tritium is produced from lithium [5]. However, there are other devices that must be also cooled: the divertor (DIV) and the vacuum vessel (VV) [1, 6], which become secondary heat sources and thus they should be used to supply additional thermal power to the power conversion system. The temperature reached in these secondary heat sources is lower, as well as the total amount of thermal power.

Two sets of heat exchangers are considered for the cooling of the BB (namely inner and outer ones). The thermal power is transferred to a heat transfer fluid (HTF) that is directed to the power conversion system to convert this thermal power into mechanical one. The HTF fluid is helium for the HCPB solution, which is heated up to 480 ºC during the pulse time [1]. Then, the helium transfers the removed thermal power to an Intermediate Heat Transfer System (IHTS) between the PHTS and the power block. In order to mitigate problems related to the cyclical operation of DEMO reactor, the IHTS can include a double-tank Energy Storage System (ESS) working with solar molten salt [3].

For each BB option, there are different solutions of Power Conversion Systems. For example, in Ref. [7] a steam Rankine cycle is proposed for the HCPB, being this kind of solution (Rankine cycles) the most reliable one. In this case, the dual tank ESS is considered. Linares et al. [5, 8] studied the use of supercritical CO_2 Brayton cycles for the case of the dual cooled lithium lead BB (another of the four considered solutions). The proposals also consider the use of an ESS. Finally, Malinowsky et al. [9, 10] also study the use of Rankine cycles but in this case for the Water-Cooled Lithium-Lead [1], likewise considering the use of a dual tank ESS.

The BB is located inside a vacuum chamber. The water-cooled vacuum vessel works at about 200 ºC to control thermal expansion [6]. The divertor is inside the vacuum chamber and it is supported by the VV. It collects most of the particles that escape the plasma confinement [6]. Two zones are found: the divertor cassette (Div-Cas), at the bottom of the VV, reaching temperatures similar to the one of the VV; and the Divertor plasma facing unit (Div-PFU), which cover the plasma chamber wall and is cooled to work at a temperature slightly lower than those of the VV and the Div-Cas [11].

The thermal level at these secondary heat sources is low, as well as the dissipated thermal power. For that reason, some of the PCS proposals consider these heat sources as waste energy [5]. However, they can contribute to increase the power rate and its introduction (instead of rejection) is advisable. Another feature of the secondary heat sources is that they also work at pulsating conditions (pulse and dwell modes). However, due to the freezing point of the molten salts, the thermal energy cannot be stored and dumped by the ESS system. Thus, the use of these heat sources conveys intermittent operation of the equipment. Up to the moment, none of the proposals considers a secondary storage system to avoid such a pulsating pattern.

The objective of this paper is the proposal of two configurations of Rankine cycles different from the standard solution considered for the DEMO 2017 design [12]. The configurations are aimed to maintain as constant as possible the operation at the pulse (120 min) and dwell (10 min) times, with minimal fluctuations of the turbine and heat exchangers parameters, in order to minimise the thermal stress of these components and ensure a reliable operation. At this regard, a secondary low temperature ESS is included to mitigate the effect of the intermittence of the secondary heat sources.

This work was done in parallel to the development of the EUROfusion project, with tasks aimed to the design of the power conversion system of DEMO. The evolution of the power conversion system of the HCPB alternative with energy storage system until 2018 and 2019 can be found in [12] and [13], respectively, and the corresponding to the WCLL can be found in [14]. Those alternatives are well accepted by the consortium and the industry. The proposals of this paper have been developed from a thermodynamic perspective and they should be understood as possible improvements to be taken into account, which may lead to a performance increase over the state of the art.

Besides, the layouts have been designed and optimised in order to maximize the power rate of the plant and to make the equipment work at the high demanding conditions during the pulse time and at low demanding conditions during the dwell time.

Section 2 shows the reference configuration and the two proposals for the PCS. Section 3 presents the methodology and main assumptions. Finally, the results and conclusions are shown in section 4 and 5, respectively.

2. Reference configuration and proposals with high and low temperature thermal storage systems.

2.1. Reference configuration.

The layout of the reference configuration is shown in Figure 1. As it is observed, the power block consists of a double tank ESS, a dual pressure level steam generator (with two levels, namely high-pressure, HP, and low-pressure, LP, ones), a steam turbine, a set of water preheaters along the feed-water line, the condenser and several pumps.

The steam generator is fed by the ESS, which supplies molten salts from the hot tank to the steam generator that, in turns, sends the molten salts to the cold tank of the ESS, once the heat has been transferred to the water/steam. Two streams of live steam are generated, one at the HP level (up to 130 bar) and the other one at the LP level (at moderate pressure around 60 bar).

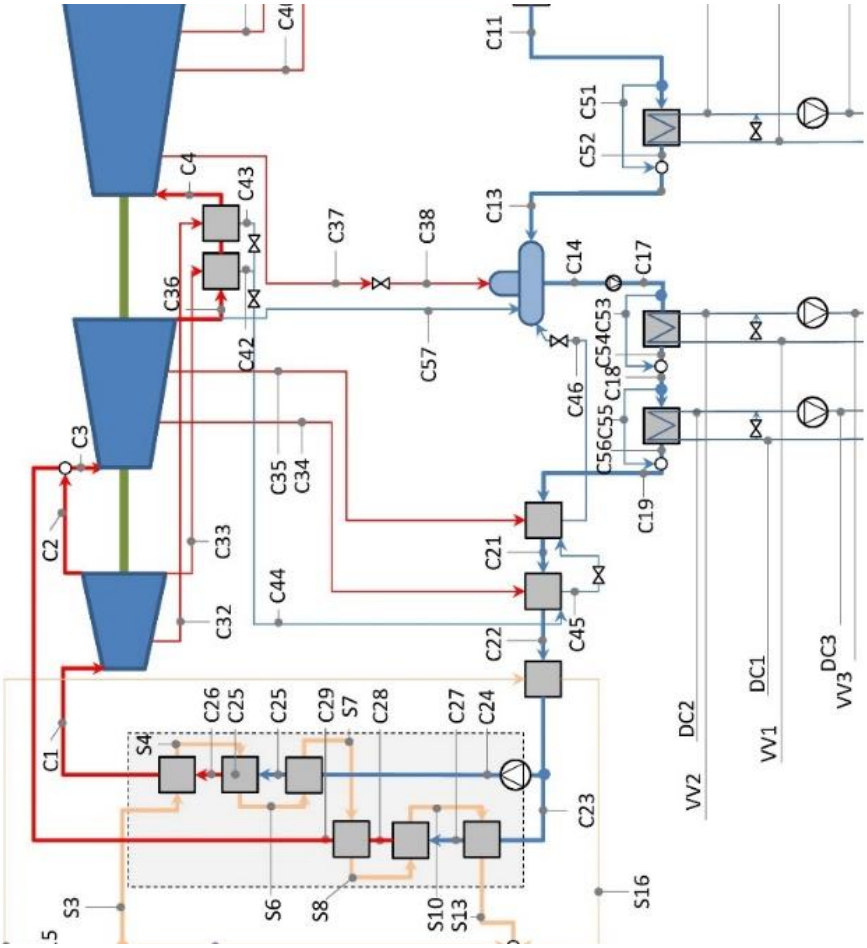

Figure 1. Layout of the reference configuration.

At pulse time, the reactor sends hot molten salts to the hot tank. A big fraction of them is sent to the steam generator while the other is stored. Besides, the molten salt pump sends cold molten salts from the cold tank to the reactor. As the mass flow of cold molten salt coming from the steam generator is lower than the mass flow that goes to the reactor, the cold tank is discharged.

At dwell time the reactor cannot supply molten salts at the required conditions and, therefore, the hot tank is discharged and the cold one is charged. Finally, as changes between pulse and dwell time do not only involve the thermal power but also the thermal conditions of the hot stream of molten salts, an auxiliary heat exchanger is required to use the residual thermal energy coming from the reactor, which only operates during the dwell time (heat exchanger fed by stream S15 in Fig. 1).The HP cylinder of steam turbine expands the high-pressure live steam (C1) from the HP level to the LP one. This cylinder contains two steam bleedings that are used to reheat the steam at the exit of the second cylinder (streams C32 and C33). The low-pressure live steam (C29) is added to the steam coming from the exit of the high-pressure cylinder and both streams (mixed at C3) are expanded into the intermediate cylinder, from the LP level to the reheating pressure level. This cylinder also includes two bleedings (C34 and C35), which are used to preheat the water that goes to the steam generator in the two last pre-heaters. Finally, the low-pressure cylinder expands the reheated steam from the reheat pressure level to the condensation pressure. In this case, three bleedings are included, the first one (C37) that feeds the deaerator and two others (C40 and C41) that are used to preheat the water at the exit of the condenser.

The feed-water line includes the corresponding heat exchangers fed by the steam extraction lines, the deaerator and three additional heat exchangers, which pre-heat the water line using the secondary heat sources of the fusion reactor: Div-PFU, VV and Div-Cas. According to the temperature hierarchy, the Div-PFU heat exchanger is placed before the deaerator while the heat exchangers corresponding to the VV and Div-Cas are placed after the deaerator. During the pulse time, the thermal power supplied by the secondary heat sources is significant. With such an arrangement, the steam mass flow coming from the extraction lines can be small during the pulse time, with the corresponding increase of mechanical power. At dwell time, the secondary heat sources cannot supply enough thermal power and the steam mass flow in the extraction lines should be significantly higher than at pulse time.

2.2. Configurations dual thermal storage systems.

The main disadvantage of the reference configuration is the variability of the working conditions between the pulse and dwell times. As commented above, the thermal power generated by the reactor is quite different in both operating modes and in the different heat sources, i.e. the main one that feeds the steam generator and the secondary ones that preheat the feed-water line.

In the case of the main heat source, the thermal power changes from about 2.2 GW at pulse to about 23 MW at dwell. This variability, which affects the steam generator, is almost completely mitigated by the thermal storage system. However, with the scheme of the reference configuration, the thermal storage system cannot completely mitigate the intermittence of the main heat source because changes not only involve the thermal power but also the temperature of the hot stream of molten salts, which makes necessary the introduction of above mentioned auxiliary heat exchanger that only works at dwell time.

The thermal power of the secondary heat sources vary from 115 MW in the Div-PFU, 86 MW in the vacuum vessel and 136 MW in the Div-Cas, to 1 MW, 1 MW and 1.4 MW, respectively. Such variations affect strongly to the feed-water line and, consequently, the extraction lines must supply extra thermal energy during the dwell time to achieve the same water conditions at the inlet of the steam generator. This extra thermal power is achieved due to a high variability of the mass flow rate extracted from the turbine. Thus, the regenerative heat exchanges must be sized to exchange a high thermal power but only during the dwell time.

The proposed configurations are aimed to maintain as constant as possible the operation regardless the operating condition, pulse and dwell times, in order to minimise the thermal stress of the components and ensure a quite reliable operation. For that reason, minimal fluctuations of the variables (i.e. mass flow rates and working temperatures) are required for all the equipment: turbine and heat exchangers of the steam cycle and the heat sources.

Besides, the layouts have been designed and optimised in order to maximize the power rate of the plant. For that reason, they include steam reheating with molten salts in the steam generator and a high number of extraction lines for the water preheating that were later reduced according to the optimisation results.

Finally, the proposed design aims to make the equipment work at the high demanding conditions during the pulse time, and at low demanding conditions during the dwell time, in order to achieve an economic coherence in terms that large equipment work during large periods, not only at the dwell time.

The configurations proposed are a dual pressure steam generator with reheat and water storage with three tanks (2P-RH-W3T) and a dual pressure steam generator with reheat, secondary storage with two tanks (2P-RH-S2T).

a) Dual pressure steam generator with reheat and water storage with three tanks (2P-RH-W3T).

Figure 2 shows the scheme of the 2P-RH-W3T configuration. Like in the reference configuration, the steam generator consists on a dual pressure one, but a reheater is included in order to reheat the steam coming from the high-pressure steam turbine up again to the maximum temperature, with the aim of maximizing the efficiency in the thermal-to-mechanical energy conversion.

The steam generator includes another proposal over the reference configuration that is the generation at the pulse time of a stream of molten salts with the same thermal level and with the same mass flow rate as the molten salts coming from the cooling loops at the dwell time (streams S16, S17 and S18 in figure 2). The integration of such externally generated stream at the pulse time inside the steam generator, at the appropriate zone according to the hierarchy of temperatures, together with the thermal storage system, allows a completely steady operation of the steam generator.

Regarding feed-water preheaters, the objective is that all of them work also in steady operation without any transition between the pulse and dwell times. For that, all the involved mass flows, pressures and temperatures should be constant. Likewise, the deaerator and all its inlets and outlets should work at the same conditions in both modes of operation.

In order to achieve such requirements, a possible solution is the introduction of a water storage system that stores hot water and releases cold water during the pulse time and, conversely, releases hot water and stores cold water during the dwell time. Thus, the storage system acts as a buffer storing and releasing the thermal energy coming from the divertor and the VV heat exchangers.

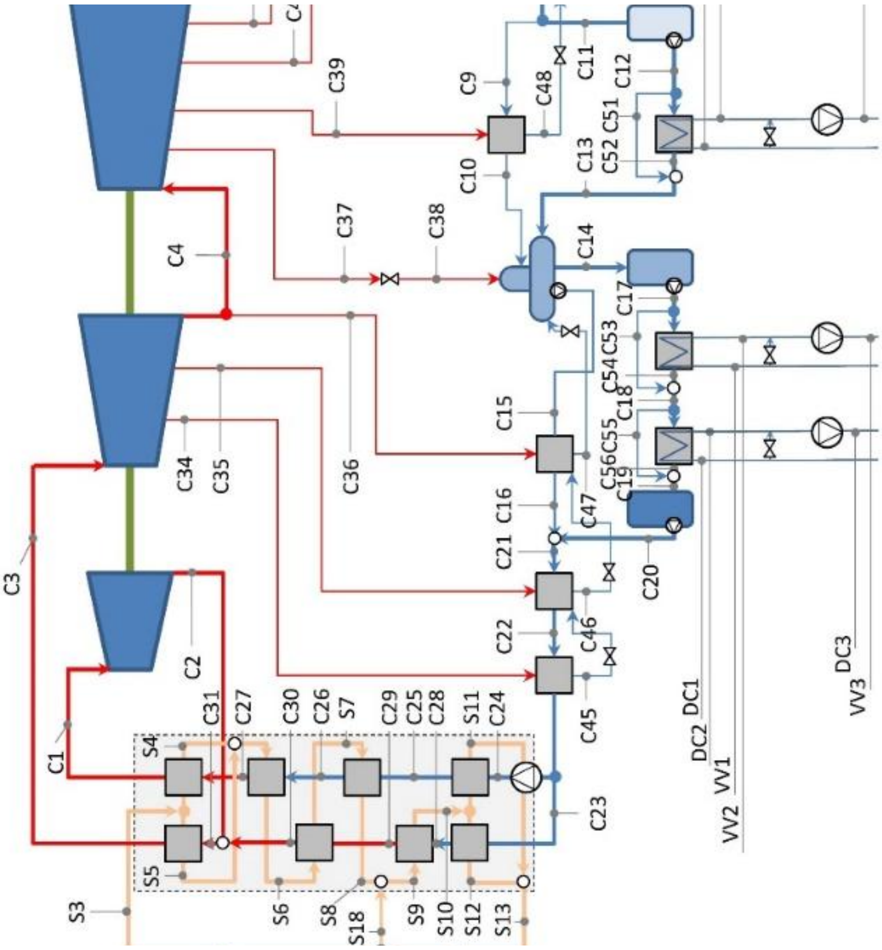

Figure 2. Layout of the 2P-RH-W3T configuration.

As it is shown in Figure 2, this storage system requires three tanks instead of two. The reason is that the ratio of thermal power from pulse to dwell times of these three heat sources (Div-CAS, VV and Div-PFU) is different one to the others, and a modulation of the feed-water mass flow rate is required to maintain the temperature of the point C13.

In order to guarantee a correct mass and energy balance in the deaerator without any difference between the pulse and dwell times, the enthalpy of the stream coming from the Div-PFU heat exchanger (C13) must be equal to that of the saturated liquid at the deaerator outlet. Following such strategy, the reduction of mass flow coming from the Div-PFU heat exchanger is balanced with an equivalent reduction of the mass flow exiting the deaerator (C14) without any repercussion on the energy balance, thanks to equality of enthalpies.

Thus, the pressure of the deaerator is reduced to 2.54 bar that, as it was commented, allows the intermediate tank to have a temperature suitable for acting as the cold tank of the Div-Cas and VV thermal storage system and, at the same time, as the cold tank of the Div-PFU thermal storage system. This pressure (and even lower) was proposed in designs preceding [12], and it is well above ambient pressure, so the deaerator can remove the eventual dissolved gases correctly.

b) Dual pressure steam generator with reheat, secondary storage with two tanks (2P-RH-S2T).

The objective of the previously presented 2P-RH-W3T configuration was to maintain the steam cycle, extraction lines and the deaerator working at the same conditions during the pulse and dwell times. However, the heat exchangers fed by the secondary heat sources have still different working conditions at the pulse and dwell times at the primary circuit.

A possibility to keep all the components of the power block working at constant operation is to store the water coming from the secondary heat sources, i.e. Div-Cas, VV and Div-PFU, instead of the feed-water of the steam cycle. The existence of three secondary heat sources with different temperatures and mass flow rates requires theoretically the introduction of six tanks of large size (due to the high mass flow rates and low temperature changes of the heating streams). For that reason, the objective was to reduce as much as possible the number and size of tanks.

The solution presented in this configuration requires the mixture of the water that circulates by the Div-CAS, VV and Div-PFU, assuming that there are no drawbacks for that, and the storage of this water in a dual tanks system. These tanks should be placed in a safe and controlled area. An additional advantage of storing the cooling water coming from these parts of the reactor is that a residence time within a tank may contribute to deactivate the water before it goes to the heat exchangers of the preheating system.

The number of tanks can be reduced from 6 to 4 if the heat coming from the Div-Cas and VV, at quite similar temperature level, are merged. In such a way, two thermal storage systems are present, one at higher temperature (corresponding to the Div-Cas and VV) and another at low temperature (corresponding to the Div-PFU). Both include a hot and a cold tank.

Moreover, if the temperature of the cold tank of the high temperature system approaches the temperature of the hot tank of the low temperature system, both tanks may be merged, removing one of them. The temperature of the cold tank of the high temperature system can be reduced if the mass flow rate of feed-water that circulates by the high temperature heat exchanger is reduced, introducing a by-pass for the corresponding heat exchanger that takes feed-water from the deaerator exit (C15 in figure 3).

Besides, the mass flow rates that charge and discharge this merged tank are quite similar but different. This difference may be removed if the temperature of the coldest tank is reduced. Such modification requires another by-pass in the feed-water system (C9 in figure 3) to reduce the mass flow incoming in the corresponding heat exchanger, to avoid very small temperature differences in the cold-end of this heat exchanger (C11). Once the requirements of equal temperature and equal discharging/charging mass flows, both tanks can be removed.

Figure 3 shows the layout of the 2P-RH-S2T configuration. As it is observed, in the mentioned by-passes the corresponding preheaters have been included.

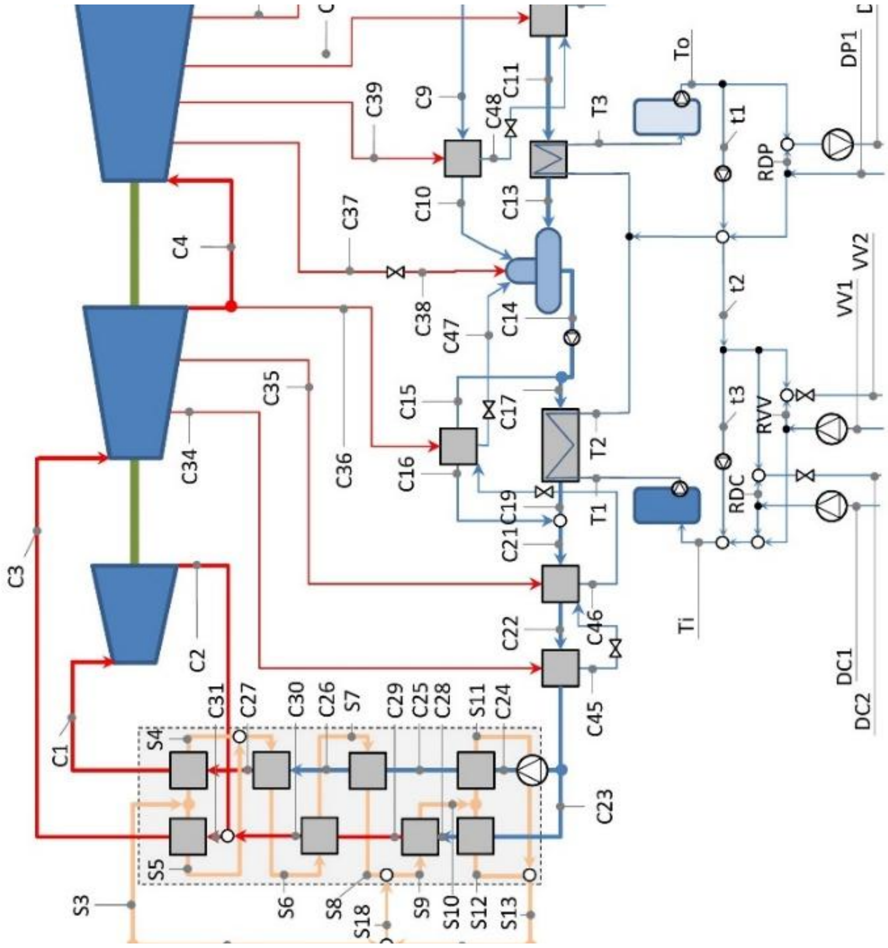

Figure 3. Layout of the 2P-RH-S2T configuration.

3. Methodology.

All the configurations have in common the thermal power, mass flows, pressures and temperatures of the streams coming from the different heat sources of the power block (which are the cooling streams of the reactor). For the simulations, mass and energy balances are accomplished for all the processes.

The energy balances for all equipment, except for the turbomachinery, can be calculated with the following equation:

$$\textstyle\sum_{inlet} \dot{m}_i \cdot h_i = \sum_{outlet} \dot{m}_i \cdot h_i \qquad (1)$$

For the turbines and pumps, the energy balance becomes:

$$\dot{W}_{turbine} = \dot{m} \cdot (h_{inlet} - h_{outlet});\ \dot{W}_{pump} = \dot{m} \cdot (h_{outlet} - h_{inlet}) \qquad (2)$$

Where $\dot{W}$ is the gross power. For the calculation, the isentropic efficiencies are required, and they are defined as below:

$$\eta_{turbine} = \Delta h / \Delta h_s\ ;\ \eta_{pump} = \Delta h_s / \Delta h \qquad (3)$$

Where Δh_s is the enthalpy variation of the isentropic process between the same inlet and outlet pressures and the same inlet conditions.

The tanks of the different thermal storage systems do not work at steady conditions, and the following mass and energy balances are accomplished:

$$(\dot{m}_{inlet} - \dot{m}_{outlet}) \cdot t_{pulse} = (\dot{m}_{outlet} - \dot{m}_{inlet}) \cdot t_{dwell} \tag{4}$$

$$(\dot{m}_{inlet} \cdot h_{inlet} - \dot{m}_{outlet} \cdot h_{outlet}) \cdot t_{pulse} = (\dot{m}_{outlet} \cdot h_{outlet} - \dot{m}_{inlet} \cdot h_{inlet}) \cdot t_{dwell} \tag{5}$$

Table 1 shows the value of the technological parameters considered, which are maintained in all configurations. The value for the maximum temperature and the pressure are imposed by the reference configuration. The minimum temperature of the feed-water at the inlet of the steam generator is set to 225 ºC to ensure a minimum temperature of the molten salt of 270 ºC, and to avoid the possibility of salt solidification at any part of the circuit. Regarding the pinch and approach points, a limit of 5 ºC was imposed in order to avoid very large equipment (economic evaluation is out of the scope of this paper). Finally, the isentropic efficiencies for the different turbomachinery take usual values for plants of several hundred MWs. The pressure of the LP evaporation and the corresponding to the turbine bleedings were optimised using a genetic algorithm.

Table 1. Technological parameters considered in the simulations.

Maximum temperature of the steam	445.82 ºC
Maximum pressure of the steam	130 bar
Minimum pinch point in the heat exchangers	5 ºC
Approach points to the drums	5 ºC
Minimum temperature of the feed-water to the steam generator	225 ºC
Isentropic efficiency of the high pressure steam turbine	88 %
Isentropic efficiency of the low pressure steam turbine	89 %
Efficiency of the pumps	75 %
Minimum quality of the steam at the turbine outlet	84 %
Electro-mechanical efficiency	97.8 %
Condensation temperature	33 ºC
Perfect thermal insulation of the heat exchangers and storage tanks	

Table 2 shows the thermal power of the different heat sources at pulse and dwell times. The high variation of the molten salt temperature is due to the intermittence of the reactor. Particularly, during the dwell time, only marginal heat is released, so the helium that cools the reactor receives less thermal power and its temperature decreases. This fact, in turns, conveys a reduction of the molten salt temperature.

Table 2. Thermal power dissipated from the reactor and temperatures of the different heat sources at pulse and dwell times.

Heat source	Thermal power		Inlet temperature		Outlet temperature	
	Pulse	Dwell	Pulse	Dwell	Pulse	Dwell
PHTS	2233 MW	22.7 MW	465 ºC	306 ºC	270 ºC	270 ºC
Div-Cas	115.2 MW	1.07 MW	210 ºC	195 ºC	180 ºC	194.7 ºC
VV	86.0 MW	1.00 MW	200 ºC	195 ºC	190 ºC	194.9 ºC
Div-PFU	136.0 MW	1.42 MW	136 ºC	133 ºC	130 ºC	132.8 ºC

The simulation model was developed in Visual Basic. The code is available in Ref. [15]. Properties for the molten salts are taken from [16], and for water-steam from [17].

Each configuration has been simulated both at pulse and dwell operation modes (the code is also available in Ref. [15]). For that, all the equipment is characterized (using hypotheses and models commonly accepted in the technical literature) taking into account the maximum capacities at which each one can operate. In the case of the reference configuration, the most demanding operation condition takes place at pulse time, except for the regenerative heat exchangers and the auxiliary molten salt heat exchanger that operates at full load during the dwell time. In the case of the proposed configurations, the maximum capacity is always required at pulse mode.

The heat exchangers, including those of the steam generator, the corresponding to the secondary heat sources and the regenerative ones, are characterized through the *UA* parameter (product of the overall heat transfer coefficient and the heat exchange area) with the following equation:

$$\dot{Q} = U \cdot A \cdot \frac{\left(\left(T_{hot,inlet} - T_{cold,outlet}\right) - \left(T_{hot,outlet} - T_{cold,inlet}\right)\right)}{\ln\left(\left(T_{hot,inlet} - T_{cold,outlet}\right) / \left(T_{hot,outlet} - T_{cold,inlet}\right)\right)} \tag{6}$$

For the evaporator (and similarly for the heat exchangers involving phase change), equation (6) becomes:

$$\dot{Q} = U \cdot A \cdot \frac{\left(T_{hot,inlet} - T_{hot,outlet}\right)}{ln\left(\left(T_{hot,inlet} - T_{saturation}\right) / \left(T_{hot,outlet} - T_{saturation}\right)\right)} \tag{7}$$

At off-design operation, the mass and heat balances are also accomplished, as well as Equation 6 or 7. However, the value of the overall heat transfer coefficient (*U*) should change because the mass flows of the fluids vary. If the thermal conductivity of the tubes is very high, the convective heat transfer coefficients vary mainly due to the mass flow change. In flows with Prandtl numbers of about 5-7, like in this case, this dependence has effect by means of an exponent of 0.8 [18]. In this work, in order to avoid a comprehensive design of the heat exchangers, the following equation is used [19]:

$$U / U_{des} = \left(\dot{m} / \dot{m}_{des}\right)^{0.8} \tag{8}$$

The mass flow rate to consider is that of the molten salts for heat exchangers of the steam generator and that of the liquid stream for the water-steam ones.

In the case of the steam turbine, each cylinder is characterized using the Stodola-Frügel law, and the corresponding constant is maintained at part load operation (equation below). This equation is used in each section, *i*, between two extractions of each cylinder of the steam turbine.

$$\dot{m}_i \cdot \sqrt{\frac{T_{i,inlet}}{p_{i,inlet}^2 - p_{i,outlet}^2}} = K_i \tag{9}$$

4. Results.

Table 3 show the main results for the reference, 2P-RH-W3T and 2P-RH-S2T configurations at pulse and dwell times. The gross power is the power generated by the steam turbines considering the electro-mechanical losses. The net power also considers the energy consumption from the pumps and other equipment of the facility. The highest consumption, particularly high at pulse mode, is due to the pumping work of the PHTS (helium blowers). These consumptions are 132.2 MW at pulse and 1.7 MW at dwell. The gross and net efficiencies are the ratio of gross or net power to total thermal energy, respectively, considering the thermal supply of all the heat sources.

First, results show that the power rates reached by the proposed configurations (2P-RH-W3T and 2P-RH-S2T) are higher than that obtained with the reference configuration. This is due to the steam reheating with molten salts in the steam generator, that allows a higher reheat temperature and, consequently, an improvement in the power generator and efficiency.

Table 3. Main results for the reference, 2P-RH-W3T and 2P-RH-S2T configurations

		Reference	2P-RH-W3T	2P-RH-S2T
Pulse	Gross power	910.1 MW	966.3 MW	965.4 MW
	Net power	752.0 MW	803.2 MW	803.0 MW
	Gross efficiency	38.0 %	40.4 %	40.4 %
	Net efficiency	31.1 %	33.6 %	33.6 %
Dwell	Gross power	926.5 MW	966.3 MW	965.4 MW
	Net power	891.0 MW	935.2 MW	933.5 MW
	Gross efficiency	41.0 %	40.4 %	40.4 %
	Net efficiency	39.4 %	39.1 %	39.0 %
Average	Gross power	911.3 MW	966.3 MW	965.4 MW
	Net power	756.2 MW	813.4 MW	813.1 MW
	Gross efficiency	38.1 %	40.4 %	40.4 %
	Net efficiency	31.6 %	34.0 %	34.0 %

Performance of 2P-RH-W3T is higher than that of 2P-RH-S2T, although both are quite similar and differences are negligible. The reasons for the differences are two. Firstly, the 2P-RH-W3T configuration has less constrains than 2P-RH-S2T, in which, as commented in previous section, the temperature of the coldest tank must be adjusted in order to design a secondary ESS with only two tanks. Secondly, the energy consumption of the pumps of the secondary heat sources is higher in the 2P-RH-S2T configuration, because the pressure of the water coming from the three secondary heat sources must be homogenised.

Finally, comparing the pulse and dwell operation, it is observed that the operation (in terms of gross power) is much steadier with the proposed configurations than with the reference one.

4.1. Reference configuration

Table 5 shows the thermodynamic state of the representative points of the reference configuration at the pulse and dwell times.

In the steam generator, thermal state of the representative points (C1, C24-C29) does not change significantly from pulse to dwell. This happen because the pressure is maintained in both pressure levels. However, there are some changes in mass flow rates. The high-pressure mass flow varies from 784 kg/s in pulse to 860 kg/s at dwell, and the low-pressure one from about 179 kg/s to 207 kg/s. In the molten salt side, changes go from about 6710 kg/s at pulse to 7366 at dwell, which is a large variation in absolute terms. On the other side, thermal state in the reheaters (C32, C33, C36, C4) vary slightly and mass flow rates are quite constants.

Table 5. Thermodynamic state and mass flow rates in the reference configuration.

	Pulse					Dwell				
Id	T (ºC)	p (bar)	h (kJ/kg)	s (kJ/kg/K)	ṁ (kg/s)	T (ºC)	p (bar)	h (kJ/kg)	s (kJ/kg/K)	ṁ (kg/s)
C1	445.8	130	3180.1	6.23	784.4	445.2	130	3178.2	6.23	859.7
C2	335.5	57.1	3009.9	6.3	662.7	329.2	57.1	2991.5	6.27	739.2
C3	316.9	51.7	2971.7	6.28	841.6	317.5	56.9	2956.2	6.21	946.3
C4	306.9	10.3	3065.7	7.14	754.8	307.0	9.9	3067.0	7.16	736.3
C5	32.9	0.05	2274.2	7.46	694.9	32.9	0.05	2279.3	7.47	634.3
C6	32.9	0.05	137.8	0.48	736.1	32.9	0.05	137.8	0.48	672.4
C7	32.9	5.7	138.5	0.48	736.1	32.9	5.7	138.5	0.48	672.4
C8	57.5	5.2	241.1	0.8	736.1	57.7	5.2	242.0	0.8	672.4
C11	63.6	4.7	266.7	0.88	736.1	64.0	4.7	268.2	0.88	672.4
C13	110.4	4.2	463.3	1.42	736.1	67.6	4.2	283.3	0.93	672.4
C14	140.8	3.7	592.7	1.75	963.4	140.8	3.7	592.7	1.75	1066.9
C17	141.9	61.1	601.0	1.75	963.4	141.9	61.1	601.0	1.75	1066.9
C18	163.2	60.6	692.8	1.97	963.4	142.6	60.6	604.1	1.76	1066.9

C19	190.8	60.1	813.1	2.24	963.4	143.0	60.1	605.8	1.76	1066.9
C21	210.5	59.6	901.4	2.42	963.4	206.5	59.6	883.2	2.38	1066.9
C22	227.1	59.1	977.5	2.58	963.4	225.8	59.1	971.3	2.56	1066.9
C23	227.1	58.6	977.4	2.58	179.0	230.6	58.6	993.6	2.61	207.1
C24	229.3	131.5	989.1	2.58	784.4	232.8	131.5	1005.3	2.62	859.7
C25	329.7	131	1522.4	3.55	784.4	329.9	131	1524.1	3.55	859.7
C26	331.2	130.5	2661.7	5.43	784.4	331.2	130.5	2661.7	5.43	859.7
C27	271.5	58.1	1192.4	2.99	179.0	271.2	58.1	1191.0	2.99	207.1
C28	273.0	57.6	2787.1	5.91	179.0	273.0	57.6	2787.1	5.91	207.1
C29	282.1	57.1	2830.4	5.99	179.0	282.1	57.1	2830.4	5.99	207.1
C32	433.7	115	3170.0	6.26	54.8	438.6	124.5	3167.8	6.23	53.5
C33	335.5	57.1	3009.9	6.3	67.0	329.2	57.1	2991.5	6.27	67.1
C34	252.3	30.0	2863.4	6.3	14.4	247.6	31.5	2841.0	6.24	25.0
C35	214.9	21.0	2799.1	6.32	37.5	214.1	20.7	2766.8	6.26	138.0
C36	185.1	11.3	2781.5	6.54	754.8	183.6	10.9	2780.3	6.56	736.3
C37	206.3	4.1	2873.8	7.19	18.8	200.5	3.7	2863.4	7.21	64.0
C38	205.4	3.7	2873.8	7.23	18.8	200.5	3.7	2570.3	7.33	7.2
C40	86.8	0.62	2577.1	7.31	8.2	84.4	0.57	2442.8	7.39	7.7
C41	63.1	0.23	2448.1	7.36	32.9	61.2	0.21	2863.4	7.21	30.4
C42	321.4	115	1471.0	3.46	54.8	321.4	115	1471.0	3.46	53.5
C43	272.4	57.1	1197.3	3	67.0	272.4	57.1	1197.3	3	67.1
C44	272.4	57.1	1320.3	3.22	121.8	272.4	57.1	1318.7	3.22	120.6
C45	220.5	30	946.1	2.52	136.2	218.0	30	934.7	2.5	145.6
C46	200.8	20	855.9	2.34	173.7	184.4	20	783.3	2.18	283.6
C49	67.5	0.56	282.6	0.92	8.2	67.7	0.56	283.4	0.93	7.7
C50	42.9	0.21	179.8	0.61	41.1	42.9	0.21	179.6	0.61	38.1
C51	63.6	4.7	266.7	0.88	0	64.0	4.7	268.2	0.88	626.2
C52	110.4	4.2	463.3	1.42	736.1	116.5	4.2	489.1	1.49	46.2
C53	141.9	61.1	601.0	1.75	0	141.9	61.1	601	1.75	1039.9
C54	163.2	60.6	692.8	1.97	963.4	170.8	60.6	725.4	2.04	27.0
C55	163.2	60.6	692.8	1.97	84.7	142.6	60.6	604.1	1.76	1057.6
C56	193.4	60.1	824.7	2.26	878.6	185.6	60.1	790.4	2.19	9.3
C57	185.1	11.3	785.6	2.19	34.9	183.6	10.9	779.3	2.17	47.0
DC1	210	34	898.1	2.42	861.1	195	34	830.7	2.28	861.1
DC2	179.8	33.8	763.5	2.13	861.1	152	33.8	642.5	1.86	9.2
DC3	180	35	764.3	2.14	861.1	194.7	35	829.4	2.28	861.1
VV1	200	31	852.9	2.33	1928.9	195	31	830.5	2.28	1928.9
VV2	178.7	30.7	758.2	2.12	933.6	166.1	30.7	703.4	2.00	26.4
VV3	190	31.5	808.3	2.23	1928.9	194.9	31.5	830.0	2.28	1928.9
DP1	136	39	574.4	1.69	5479.8	133	39	561.6	1.66	5479.8
DP2	89.2	38.8	376.8	1.18	731.9	80.5	38.8	340.1	1.08	46.0
DP3	130	50	549.6	1.63	5479.8	132.8	50	561.4	1.66	5479.8
CD1	20	1	84.0	0.30	50000	20	1	84.0	0.30	45144
CD2	27.1	1	113.7	0.40	50000	27.2	1	114.1	0.40	45144
S1	465.2		726.7		7338.3	306.2		478.2		420.7
S2	465.2		726.7		7338.3	306.2		478.2		0
S3	465.2		726.7		6710.0	465.2		726.7		7366.2
S4	426.4		666.1		6710.0	426.6		666.4		7366.2
S6	341.2		532.9		6710.0	341.6		533.6		7366.2
S7	301.2		470.5		6710.0	302.8		473.0		7366.2
S8	300.5		469.4		6710.0	302.1		471.8		7366.2
S10	273.3		426.9		6710.0	273.3		426.9		7366.2
S13	269.6		421.1		6710.0	269.8		421.4		7366.2
S14	270.2		422.0		7338.3	271.6		422.4		420.7
S15	465.2		726.7		0.0	306.2		478.2		420.7
S16	270.0		421.7		0.0	270.0		421.7		420.7
S17	465.2		726.7		13.8	465.2		726.7		8.9
S18	270.0		421.7		6723.8	270.0		421.7		7375.1

Regarding the feed-water line, thermal states in the pumps and preheaters vary slightly or do not vary, except for the inlet temperature of preheater 3 (C19) that changes from 191 ºC (pulse) to 142 ºC (dwell). Changes in mass flow rates are higher, particularly in preheaters 3 and 4, which varies from about 963 kg/s to 1.067 kg/s at the feed-water side (C21, C22), and from about 37 kg/s to 138 kg/s (C35) and 14 kg/s to 25 kg/s (C34) at the steam extraction lines side. Variation in preheaters 1 and 2 is lower (736 kg/s to 672 kg/s at the feed-water side (C7, C8) and lower at the steam extraction line side (C40, C41)). Mass flow in the drain before the reheat (C57) varies from 37 kg/s to 47 kg/s. Finally, the preheater fed by molten salts (S15, S16) is deactivated at pulse mode and allows a temperature increase of the feed-water of 5 ºC at dwell.

The temperature of the feed-water that enters to the deaerator (C13) varies from 110 ºC to 68 ºC, and mass flow rates coming from the turbine bleedings changes significantly: one of them from 19 kg/s to 7 kg/s (C38) and the other from 174 kg/s to 284 kg/s (C46). The water exiting the deaerator (C14) maintains almost constant its temperature and the mass flow rate changes from 963 kg/s to 1067 kg/s.

Regarding the heat exchanges of the secondary heat sources, thermal conditions changes moderately. The highest variation takes place in the inlet temperature (feed-water side) of the Div-Cas heat exchanger (C18), which varies from 163 ºC to 143 ºC. Mass flow rates change strongly in the three heat exchangers: from 732 kg/s to 46 kg/s in Div-PFU (DP2); from 934 kg/s to 26 kg/s in VV (VV2); and from 861 kg/s to 9 kg/s in Div-Cas (DC2).

Finally, the thermal states of most of the representative points of the molten salt circuits do not present any variation. However, mass flow rates present high variations. The mass flow of the hot molten salt pump changes from 6710 kg/s to 7366 kg/s. The mass flow rate in the cold molten salt pump is much higher, varying from 7338 kg/s to 420 kg/s. The dwell bypass is closed at pulse time and works at a rate of about 420 kg/s at dwell time.

4.2. 2P-RH-W3T configuration

Table 6 shows the thermodynamic state of the representative points of the 2P-RH-W3T configuration at the pulse and dwell times.

Like in the reference configuration, thermal state of representative points of the molten salts circuit does not change. Variation of the mass flow rate of the hot molten salt pump is below 3%. The behaviour of the cold molten salt pump, dwell bypass, hot bypass and cold bypass are similar to the reference configuration. The preheater fed by molten salt during the dwell time is not required and it can be removed.

Table 6. Thermodynamic state and mass flow rates in the 2P-RH-W3T configuration.

	Pulse					Dwell				
Id	T (ºC)	p (bar)	h (kJ/kg)	s (kJ/kg/K)	ṁ (kg/s)	T (ºC)	p (bar)	h (kJ/kg)	s (kJ/kg/K)	ṁ (kg/s)
C1	445.8	130	3180.1	6.23	648.2	445.8	130	3180.1	6.23	648.2
C2	330.8	57.6	2994.7	6.27	648.2	330.8	57.6	2994.7	6.27	648.2
C3	445.8	57.1	3296.8	6.73	853.9	445.8	57.1	3296.8	6.73	853.9
C4	219.5	9.1	2878.7	6.84	771.5	219.5	9.1	2878.7	6.84	771.5
C5	32.9	0.05	2173.1	7.13	705.0	32.9	0.05	2173.1	7.13	705.0
C6	32.9	0.05	137.8	0.48	764.7	32.9	0.05	137.8	0.48	764.7
C7	32.9	4.54	138.4	0.48	764.7	32.9	4.54	138.4	0.48	764.7
C8	62.7	4.04	262.7	0.86	764.7	62.7	4.04	262.7	0.86	764.7
C9	75.6	3.54	316.6	1.02	156.9	75.6	3.54	316.6	1.02	156.9
C10	100.4	3.04	420.8	1.31	156.9	100.4	3.04	420.8	1.31	156.9
C11	75.6	3.54	316.6	1.02	607.7	75.6	3.54	316.6	1.02	607.7
C12	75.6	3.54	316.6	1.02	654.6	75.6	3.54	316.6	1.02	46.1
C13	127.9	3.04	537.6	1.61	654.6	127.9	3.04	537.6	1.61	46.1
C14	127.9	2.54	537.6	1.61	763.1	127.9	2.54	537.6	1.61	763.1
C15	129.0	61.1	545.9	1.62	137.7	129.0	61.1	545.9	1.62	137.7
C16	175.8	60.1	747.2	2.09	137.7	175.8	60.1	747.2	2.09	137.7
C17	128.2	16.0	539.5	1.61	780.9	128.2	16.0	539.5	1.61	19.5
C18	156.1	15.5	659.1	1.90	780.9	156.1	15.5	659.1	1.90	19.5
C19	190.0	15.0	807.5	2.24	780.9	190.0	15.0	807.5	2.24	19.5
C20	191.1	60.1	814.4	2.24	716.3	191.1	60.1	814.4	2.24	716.3
C21	187.7	59.6	799.7	2.21	853.9	187.7	59.6	799.7	2.21	853.9
C22	211.9	59.1	907.6	2.44	853.9	211.9	59.1	907.6	2.44	853.9
C23	233.6	59.1	1007.6	2.64	648.2	233.6	59.1	1007.6	2.64	648.2

C24	235.8	132	1019.3	2.64	648.2	235.8	132	1019.3	2.64	648.2
C25	268.5	131.5	1175.6	2.94	648.2	268.5	131.5	1175.6	2.94	648.2
C26	326.2	131.0	1498.1	3.51	648.2	326.2	131.0	1498.1	3.51	648.2
C27	331.2	130.5	2661.7	5.43	205.7	331.2	130.5	2661.7	5.43	205.7
C28	268.5	58.6	1177.3	2.96	205.7	268.5	58.6	1177.3	2.96	205.7
C29	273.5	58.1	2786.6	5.91	205.7	273.5	58.1	2786.6	5.91	205.7
C30	326.2	57.6	2980.6	6.25	648.2	326.2	57.6	2980.6	6.25	648.2
C31	329.7	57.6	2991.3	6.27	853.9	329.7	57.6	2991.3	6.27	853.9
C34	355.4	29.9	3129.2	6.77	39.2	355.4	29.9	3129.2	6.77	39.2
C35	304.4	19.8	3034.9	6.79	40.0	304.4	19.8	3034.9	6.79	40.0
C36	219.5	9.1	2878.7	6.84	3.2	219.5	9.1	2878.7	6.84	3.2
C37	127.9	2.54	2661.8	6.91	6.8	127.9	2.54	2661.8	6.91	6.8
C38	127.9	2.54	2661.8	6.91	6.8	127.9	2.54	2661.8	6.91	6.8
C39	105.5	1.23	2554.6	6.95	7.5	105.5	1.23	2554.6	6.95	7.5
C40	81.8	0.51	2436.3	7	19.1	81.8	0.51	2436.3	7	19.1
C41	67.7	0.28	2363.3	7.03	33.1	67.7	0.28	2363.3	7.03	33.1
C45	221.9	29.9	952.4	2.53	39.2	221.9	29.9	952.4	2.53	39.2
C46	197.7	19.8	842.3	2.31	79.3	197.7	19.8	842.3	2.31	79.3
C47	139.0	9.1	585.1	1.73	82.5	139.0	9.1	585.1	1.73	82.5
C48	85.6	1.23	358.4	1.14	7.5	85.6	1.23	358.4	1.14	7.5
C49	72.7	0.51	304.3	0.99	26.6	72.7	0.51	304.3	0.99	26.6
C50	42.9	0.28	179.8	0.61	59.7	42.9	0.28	179.8	0.61	59.7
C51	75.6	3.54	316.6	1.02	0	75.6	3.54	316.6	1.02	46.2
C52	127.9	3.04	537.6	1.61	654.6	127.9	3.04	537.6	1.61	46.2
C53	129.0	16.0	545.9	1.62	0	129.0	16.0	545.9	1.62	19.5
C54	156.1	15.5	659.1	1.90	780.9	169.8	15.5	718.6	2.04	19.5
C55	156.1	15.5	659.1	1.90	0	169.8	15.5	718.6	2.04	19.5
C56	190.0	15.0	807.5	2.24	780.9	190.0	15.0	807.5	2.24	19.5
DC1	210.0	34	898.1	2.42	861.1	195	34	830.7	2.28	861.1
DC2	176.1	33.8	747.1	2.10	861.1	171.5	33.8	726.9	2.05	16.7
DC3	180.0	35	764.3	2.14	861.1	194.6	35	829.4	2.28	861.1
VV1	200.0	31	852.9	2.33	1928.9	195	31	830.5	2.28	1928.9
VV2	172.9	30.7	732.58	2.07	736.3	140.1	30.7	591.3	1.74	14.0
VV3	190.0	31.5	808.3	2.23	1928.9	194.6	31.5	830.0	2.28	1928.9
DP1	136.0	39	574.4	1.69	5479.8	133	39	561.6	1.66	5479.8
DP2	83.6	38.8	353.3	1.12	654.2	80.3	38.8	339.4	1.08	45.9
DP3	130.0	50	549.6	1.63	5479.8	132.6	50	561.4	1.66	5479.8
CD1	20.0	1	84.0	0.30	50000	20	1	84.0	0.30	50000
CD2	26.9	1	113.7	0.40	50000	26.9	1	114.1	0.39	50000
S1	465.2		726.7		7338.3	306.2		478.2		420.7
S2	465.2		726.7		7338.3	306.2		478.2		0
S3	465.2		726.7		6702.0	465.2		726.7		6702.0
S4	408.2		637.6		3773.0	408.2		637.6		3773.0
S5	408.2		637.6		2929.0	408.2		637.6		2929.0
S6	336.2		525.1		6702.0	336.2		525.1		6702.0
S7	332.3		519.1		6702.0	332.3		519.1		6702.0
S8	312.4		487.9		6702.0	312.4		487.9		6702.0
S9	312.0		487.4		7122.6	312.0		487.4		7122.6
S10	282.2		440.9		7122.6	282.2		440.9		7122.6
S11	270.0		421.7		5296.4	270.0		421.7		5296.4
S12	270.0		421.7		1826.3	270.0		421.7		1826.3
S13	270.0		421.7		7122.6	270.0		421.7		7122.6
S14	270.2		672.1		7338.3	270.2		672.1		7338.3
S15	465.2		726.7		0.0	306.2		726.7		420.7
S16	465.2		726.7		77.9	465.2		726.7		0
S17	270.0		421.7		342.8	270.0		421.7		0
S18	306.2		478.2		420.7	306.2		478.2		420.7

In the steam generator of 2P-RH-W3T configuration, all the thermal states and mass flows are maintained and there are not any differences either in the water-steam side or in the molten salt side in both modes of operation.

Thermal states in the feed-water line are maintained constant because of the steady conditions in the steam turbine. All the preheaters work at steady conditions without changes from pulse to dwell. There are some variations in the mass flow rate of the pumps of the low (C12) and intermediate (C17) temperature tanks, changing respectively from about 655 kg/s (pulse) to 46 kg/s (dwell); and from 781 kg/s (pulse) to 20 kg/s (dwell). These variations are high in relative terms but, in absolute terms, they are lower than the differences in the molten salt pumps.

The deaerator also works at steady conditions all time, without variations of the thermal states. Mass flow rates are also constant except for the feed-water coming from the Div-PFU heat exchanger (C13), which varies from 655 kg/s (pulse) to 46 kg/s (dwell). This change has not any effect in the heat balance because the enthalpy of this stream is always the same as that of the water exiting the deaerator (C14), whose mass flow rate changes accordingly.

Finally, as in the reference case, the thermal conditions of the heat exchanges of the secondary heat sources changes moderately. Also, like in previous case, mass flow rates change strongly: from 650 kg/s to 46 kg/s in Div-PFU (DP2), from 736 kg/s to 14 kg/s in VV (VV2) and from 861 kg/s to 17 kg/s in Div-CAS (DC2).

The inventory of mass to store in the tanks are 465 ton for the hot one (at 15 bar), 128 ton for the intermediate one (at 2.5 bar) and 337 ton for the cold one (at 4 bar), values significantly lower than the main ESS using molten salts (over 4000 ton). It is important to note that the tanks, although not very large, consume some space and they must be allocated inside the building, issue that is not possible in the current accepted designs for DEMO. The cost that this extra space conveys is not accounted for as the economical aspects have not been considered.

To sum up, 2P-RH-W3T configuration presents a steady behaviour of almost all the equipment of the steam cycle. Additionally, all the equipment (particularly the feed-water preheaters) is designed to operate at nominal conditions either at pulse and dwell modes or at pulse mode, avoiding the sizing of any equipment only for the dwell time (which is very short). The components that change their operating conditions present a range of variation similar or lower than in the reference configuration, and the control strategy should be simpler than in reference configuration due to the steadier operation.

Regarding the power rate, the value reached is slightly higher than in the reference case due to the reheat up to a higher temperature (446 ºC instead of 307 ºC).

4.3. 2P-RH-S2T configuration

Table 7 shows the thermodynamic state of the representative points of the 2P-RH-S2T configuration at the pulse and dwell times.

Table 7. Thermodynamic state and mass flow rates in the 2P-RH-S2T configuration.

	Pulse					Dwell				
Id	T (ºC)	p (bar)	h (kJ/kg)	s (kJ/kg/K)	ṁ (kg/s)	T (ºC)	p (bar)	h (kJ/kg)	s (kJ/kg/K)	ṁ (kg/s)
C1	445.8	130	3180.1	6.23	648.2	445.8	130	3180.1	6.23	648.2
C2	330.8	57.6	2994.7	6.27	648.2	330.8	57.6	2994.7	6.27	648.2
C3	445.8	57.1	3296.8	6.73	853.6	445.8	57.1	3296.8	6.73	853.6
C4	216.8	8.8	2873.9	6.84	771.5	216.8	8.8	2873.9	6.84	771.5
C5	32.9	0.05	2173.1	7.13	695.6	32.9	0.05	2173.1	7.13	695.6
C6	32.9	0.05	137.8	0.48	770.5	32.9	0.05	137.8	0.48	770.5
C7	32.9	4.54	138.4	0.48	770.5	32.9	4.54	138.4	0.48	770.5
C8	58.9	4.54	247.0	0.82	738.3	58.9	4.54	247.0	0.82	738.3
C9	58.9	4.54	247.0	0.82	32.2	58.9	4.54	247.0	0.82	32.2
C10	81.9	3.04	343.2	1.1	32.2	81.9	3.04	343.2	1.1	32.2
C11	85.0	3.54	356.0	1.13	738.3	85.0	3.54	356.0	1.13	738.3
C13	128.0	3.04	537.9	1.61	738.3	128.0	3.04	537.9	1.61	738.3
C14	127.9	2.54	537.6	1.61	853.6	127.9	2.54	537.6	1.61	853.6
C15	129.0	62.1	546.1	1.62	137.1	129.0	62.1	546.1	1.62	137.1

C16	174.6	61.1	742.2	2.08	137.1	174.6	61.1	742.2	2.08	137.1
C17	129.0	62.1	546.1	1.62	716.5	129.0	62.1	546.1	1.62	716.5
C19	190.0	61.1	809.8	2.23	716.5	190.0	61.1	809.8	2.23	716.5
C21	187.5	61.1	799.0	2.21	853.6	187.5	61.1	799.0	2.21	853.6
C22	210.4	60.6	901.1	2.42	853.6	210.4	60.6	901.1	2.42	853.6
C23	233.4	60.1	1006.7	2.64	205.3	233.4	60.1	1006.7	2.64	205.3
C24	235.6	132	1018.4	2.64	648.2	235.6	132	1018.4	2.64	648.2
C25	268.5	131.5	1175.5	2.94	648.2	268.5	131.5	1175.5	2.94	648.2
C26	326.2	131	1498.1	3.51	648.2	326.2	131	1498.1	3.51	648.2
C27	331.2	130.5	2661.7	5.43	648.2	331.2	130.5	2661.7	5.43	648.2
C28	268.5	58.6	1177.3	2.96	205.3	268.5	58.6	1177.3	2.96	205.3
C29	273.5	58.1	2786.6	5.91	205.3	273.5	58.1	2786.6	5.91	205.3
C30	326.2	57.6	2980.6	6.25	205.3	326.2	57.6	2980.6	6.25	205.3
C31	329.7	57.6	2991.3	6.27	853.6	329.7	57.6	2991.3	6.27	853.6
C34	355.0	29.8	3128.4	6.77	41.3	355.0	29.8	3128.4	6.77	41.3
C35	301.0	19.2	3028.7	6.79	37.9	301.0	19.2	3028.7	6.79	37.9
C36	216.8	8.8	2873.9	6.84	2.9	216.8	8.8	2873.9	6.84	2.9
C37	127.9	2.54	2662.0	6.91	1.0	127.9	2.54	2662.0	6.91	1.0
C38	127.9	2.54	2662.0	6.91	1.0	127.9	2.54	2662.0	6.91	1.0
C39	91.9	0.75	2487.7	6.97	1.4	91.9	0.75	2487.7	6.97	1.4
C40	90.0	0.70	2478.1	6.98	36.8	90.0	0.70	2478.1	6.98	36.8
C41	63.9	0.24	2343.4	7.04	36.8	63.9	0.24	2343.4	7.04	36.8
C45	220.4	29.8	945.8	2.52	41.3	220.4	29.8	945.8	2.52	41.3
C46	197.5	19.2	841.5	2.31	79.2	197.5	19.2	841.5	2.31	79.2
C47	139.0	8.8	585.2	1.73	82.1	139.0	8.8	585.2	1.73	82.1
C48	68.9	0.75	288.5	0.94	1.4	68.9	0.75	288.5	0.94	1.4
C49	68.9	0.70	288.5	0.94	38.2	68.9	0.70	288.5	0.94	38.2
C50	42.9	0.24	179.8	0.61	74.9	42.9	0.24	179.8	0.61	74.9
T1	195.0	38.8	830.9	2.28	701.8	195.0	38.8	830.9	2.28	701.8
T2	133.0	38.8	561.6	1.66	701.8	133.0	38.8	561.6	1.66	701.8
T3	90.0	38.8	379.8	1.19	738.8	90.0	38.8	379.8	1.19	738.8
to	90.0	38.8	379.8	1.19	795.6	90.0	38.8	379.8	1.19	55.9
t1	90.0	38.8	379.8	1.19	52.3	90.0	38.8	379.8	1.19	0
t2	133.0	38.8	561.6	1.66	758.7	133.3	38.8	563.0	1.67	19.0
t3	133.0	38.8	561.6	1.66	112.7	133.3	38.8	563.0	1.67	0
ti	195.0	38.8	830.9	2.28	758.7	195.0	38.8	830.9	2.28	19.0
DC1	210.0	34	898.1	2.42	861.1	195.0	34	830.7	2.28	861.1
DC2	180.0	35	764.2	2.14	861.1	194.7	35	829.3	2.28	861.1
RDC	210.1	39	898.8	2.42	517.4	195.1	39	831.3	2.28	854.6
VV1	200.0	31	852.9	2.33	1928.9	195.0	31	830.5	2.28	1928.9
VV2	190.0	31.5	808.1	2.23	1928.9	194.8	31.5	829.9	2.28	1928.9
RVV	200.2	39	854.0	2.33	1626.6	195.2	39	831.6	2.28	1916.4
DP1	136.0	39	574.4	1.69	5479.8	133.0	39	561.6	1.66	5479.8
DP2	130.0	50	549.5	1.63	5479.8	132.7	50	561.2	1.66	5479.8
RDP	136.0	39	574.4	1.69	4736.5	133.0	39	561.6	1.66	5423.5
CD1	20.0	1	84.0	0.30	50000	20.0	1	84.0	0.30	50000
CD2	26.9	1	113.7	0.40	50000	26.9	1	113.7	0.40	50000
S1	465.2		726.7		7338.3	306.2		478.2		420.7
S2	465.2		726.7		7338.3	306.2		478.2		0
S3	465.2		726.7		6702.0	465.2		726.7		6702.0
S4	408.2		637.6		3773.6	408.2		637.6		3773.6
S5	408.2		637.6		2928.4	408.2		637.6		2928.4
S6	336.2		525.1		6702.0	336.2		525.1		6702.0
S7	332.4		519.1		6702.0	332.4		519.1		6702.0
S8	312.4		487.9		6702.0	312.4		487.9		6702.0
S9	312.0		487.4		7122.6	312.0		487.4		7122.6
S10	282.3		441.0		7122.6	282.3		441.0		7122.6
S11	270.0		421.7		5299.7	270.0		421.7		5299.7
S12	270.0		421.7		1822.9	270.0		421.7		1822.9
S13	270.0		421.7		7122.6	270.0		421.7		7122.6
S14	270.2		672.1		7338.3	270.2		672.1		7338.3
S15	465.2		726.7		0.0	306.2		726.67		420.7
S16	465.2		726.7		77.9	465.2		726.67		0
S17	270.0		421.7		342.8	270.0		421.74		0
S18	306.2		478.2		420.7	306.2		478.2		420.7

In the molten salts circuit, thermal state and mass flow variations are qualitatively the same as in 2P-RH-W3T. Thermal states are constant and mass flow rates change only in the cold molten salt pump and the dwell (S15) bypass and hot and cold bypasses (S16, S17) in a similar magnitude as previous configurations.

Similarly to 2P-RH-W3T, the steam generator works at completely steady conditions in both modes of operation, pulse and dwell. Also, conditions in the feed-water line are maintained, both thermal states and mass flow rates. In this case, as the tanks are not in the feed-water side, pumps also work without any variation. The deaerator works at steady conditions without variations of temperature, pressure and mass flow in any inlet or outlet stream.

Regarding the heat exchangers of the secondary heat sources, in this case there are only two, one at the temperature levels of the Div-PFU and the other at the temperature levels of the VV and Div-Cas. Both heat exchangers work also without variations in pulse and dwell mode, thanks to the thermal storage of the water coming from de divertor and vacuum vessel (points T1, T2, T3, C11, C13, C17 and C19).

This configuration requires a water circuit to manage thermal storage. This circuit consists of a cold line (t1, t2 and t3) and three recirculation streams to control the temperature of the water that returns to the Div-PFU (RDP), VV (RVV) and Div-Cas (RDC).

The cold line serves 113 kg/s to the high temperature heat sources (t3); and 52 kg/s to the low temperature heat source (t1) at pulse; and it is closed at dwell. Its temperature is constant.

The Div-PFU water recirculation (RDP) changes from 4737 kg/s to 5424 kg/s. VV recirculation (RVV) changes from 1627 kg/s to 1916 kg/s. Div-Cas recirculation (RDC) changes from 517 kg/s to 855 kg/s. All these mass flow variations are significant, but the range is similar or lower than in other equipment (molten salt or water) of the reference and 2P-RH-W3T configurations.

Temperature variations are low or null. Besides, the pump placed in the cold tank works at 796 kg/s in pulse and 56 kg/s at dwell (to), which is a variation similar to that of pumps of other configurations. The pump of the hot tank works at constant operation (ti).

The mass inventory to store in the secondary ESS is 410 ton. This feature is particularly significant for the HCPB concept, where the use of water is minimised to avoid tritium permeation into the cooling system. Therefore, this proposal would require of a detailed analysis to check the degree of contamination.

To sum up, this configuration presents the steadiest behaviour. All the equipment work without changes from pulse to dwell, except for some recirculation lines and a pump, whose variation rage is similar or lower than in other configurations.

5. Conclusions.

This paper proposes two Rankine cycle configurations different from the standard solution considered for the DEMO 2017 design using the Helium Cooled Pebble Bed (HCPB) Breeding Blanket. The aim of the configurations is to reach a quasi-steady operation from pulse and dwell times, trying to avoid temperature, pressure and mass flow variation in the main components of the facility, and using equipment commonly used in industry. For that, both configurations include an auxiliary thermal storage system for the feed-water line or secondary heat sources.

For this purpose, several cycle configurations have been analysed including some options postulating a modification of divertor and vacuum vessel loop inventory/lay-out, whose viability however should be analysed also from the point of view of systems design objectives and overall plant safety.

The first configuration, namely 2P-RH-W3T, stores water from the feed-water line. It uses three tanks that require about 500 ton of additional water inventory. Compared to the reference configuration, temperature and pressure in the components are much steadier, and mass flow rates in the steam generator and preheaters are constant. Mass flow rates in the molten salt circuits, pumps and heat exchangers of secondary heat sources vary in a similar range of values.

The second configuration, namely 2P-RH-S2T, stores water coming from the divertor and vacuum vessel into two tanks. It allows a completely steady operation of all the components. The inventory of water coming from the reactor is 410 ton.

In summary, it is possible to ensure a completely constant and steady operation of the whole steam cycle, including all the heat exchangers, without differences between the pulse and dwell modes using two secondary storage tanks additional to the two original molten salt ones for the main heat supply. Additionally, the feed-water system is in contact with more deactivated cooling water. Besides, power rate in all cases is higher than in the reference configuration due to the higher reheating temperature (446 ºC instead of 310 ºC).

6. Acknowledgements.

The work has been done within the EUROfusion Consortium framework. It has received funding from the Euratom Research and Training Programme 2014-2018 under grant Nº 633053.

References

[1]. Barucca L et al. Status of EU DEMO heat transport and power conversion systems. Fusion Engineering and Design 136 (2018) 1557–1566. DOI:10.1016/j.fusengdes.2018.05.057

[2]. Federici G et al. DEMO design activity in Europe: Progress and updates. Fusion Engineering and Design 136 (2018) 729–741. DOI: 10.1016/j.fusengdes.2018.04.001.

[3]. Federici G et al. Overview of the design approach and prioritization of R&D activities towards an EU DEMO, Fusion Eng. Des. 109–111 (2016) 1464–1474. DOI: 10.1016/j.fusengdes.2015.11.050

[4]. Cismondi F et al. Progress in EU Breeding Blanket design and integration. Fusion Engineering and Design 136 (2018) 782–792. DOI: 10.1016/j.fusengdes.2018.04.009.

[5]. Linares JI et al. Recuperated versus single-recuperator re-compressed supercritical CO2 Brayton power cycles for DEMO fusion reactor based on dual coolant lithium lead blanket. Energy 140 (2017) 307-317. DOI: 10.1016/j.energy.2017.08.105.

[6]. Bachmann C et al. Initial DEMO tokamak design configuration studies. Fusion Engineering and Design 98–99 (2015) 1423–1426. DOI: 10.1016/j.fusengdes.2015.05.027.

[7]. Bubelis E, Hering W, Perez-Martin S. Conceptual designs of PHTS, ESS and PCS for DEMO BoP with helium cooled BB concept. Fusion Engineering and Design 136 (2018) 367–371. DOI: 10.1016/j.fusengdes.2018.02.040.

[8]. Linares JI, et al. Supercritical CO2 Brayton power cycles for DEMO (demonstration power plant) fusion reactor based on dual coolant lithium lead blanket. Energy 98 (2016) 271-283. DOI: 10.1016/j.energy.2016.01.020.

[9]. Malinowski L, Lewandowska M, Giannetti F. Analysis of the secondary circuit of the DEMO fusion power plantusing GateCycle. Fusion Engineering and Design 124 (2017) 1237–1240. DOI: 10.1016/j.fusengdes.2017.03.026.

[10]. Malinowski L, Lewandowska M, Giannetti F. Design and analysis of a new configuration of secondary circuit of the EUDEMO fusion power plant using GateCycle. Fusion Engineering and Design 136 (2018) 1149–1152. DOI: 10.1016/j.fusengdes.2018.04.091.

[11]. Barrett TR, et al. Progress in the engineering design and assessment of the European DEMO first wall and divertor plasma facing components. Fusion Eng. Des. 109–111 (2016) 917–924. DOI: 10.1016/j.fusengdes.2016.01.052.

[12]. Bubelis E, Hering W, Perez-Martin S. Industry supported improved design of DEMO BoP for HCPB BB concept with energy storage system. Fusion Engineering and Design, in press. DOI: 10.1016/j.fusengdes.2019.03.183.

[13]. Bubelis E, Hering W. DEMO 16 sectors. HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS+ESS – Conceptual designs and sizing of PHTS, IHTS, ESS and PCS components. EFDA D_2MH7AQ. Final report on deliverable BOP-2.1-T022-D001. 2019.

[14]. Palazzo P, Giannetti F, Caruso G. A Preliminary Exergy Analysis of the EU DEMO Fusion Reactor. Italian Journal of Engineering Science 63 (2019) 437-446. DOI: 10.18280/ti-ijes.632-447.

[15]. Serrano-Lópeza R, Fradera J, Cuesta-López S. Molten salts database for energy applications. Chemical Engin & Processing: Process Intensification 73 (2013) 87-102. DOI: 10.1016/j.cep.2013.07.008.

[16]. Wagner W, Pruss A. The IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use. J. Phys. Chem. Ref. Data, 31(2):387-535, 2002. DOI: 10.1063/1.1461829.

[17]. [dataset] Rovira A, Sánchez C. Data for: Proposal of optimized power cycles for the DEMO power plant (EUROfusion). Mendeley Data, 2019.

[18]. Rohsenow WM, Hartnett JP, Ganic EN. Handbook of heat transfer fundamentals, 2nd edition, MacGraw-Hill Book Company, USA, 1985.

[19]. Rovira A, et al. On the improvement of annual performance of solar thermal power plants through exergy management. International Journal of Energy Research 38 (2014), 658-673. DOI: 10.1002/er.3075.

Figure 1

Click here to download high resolution image

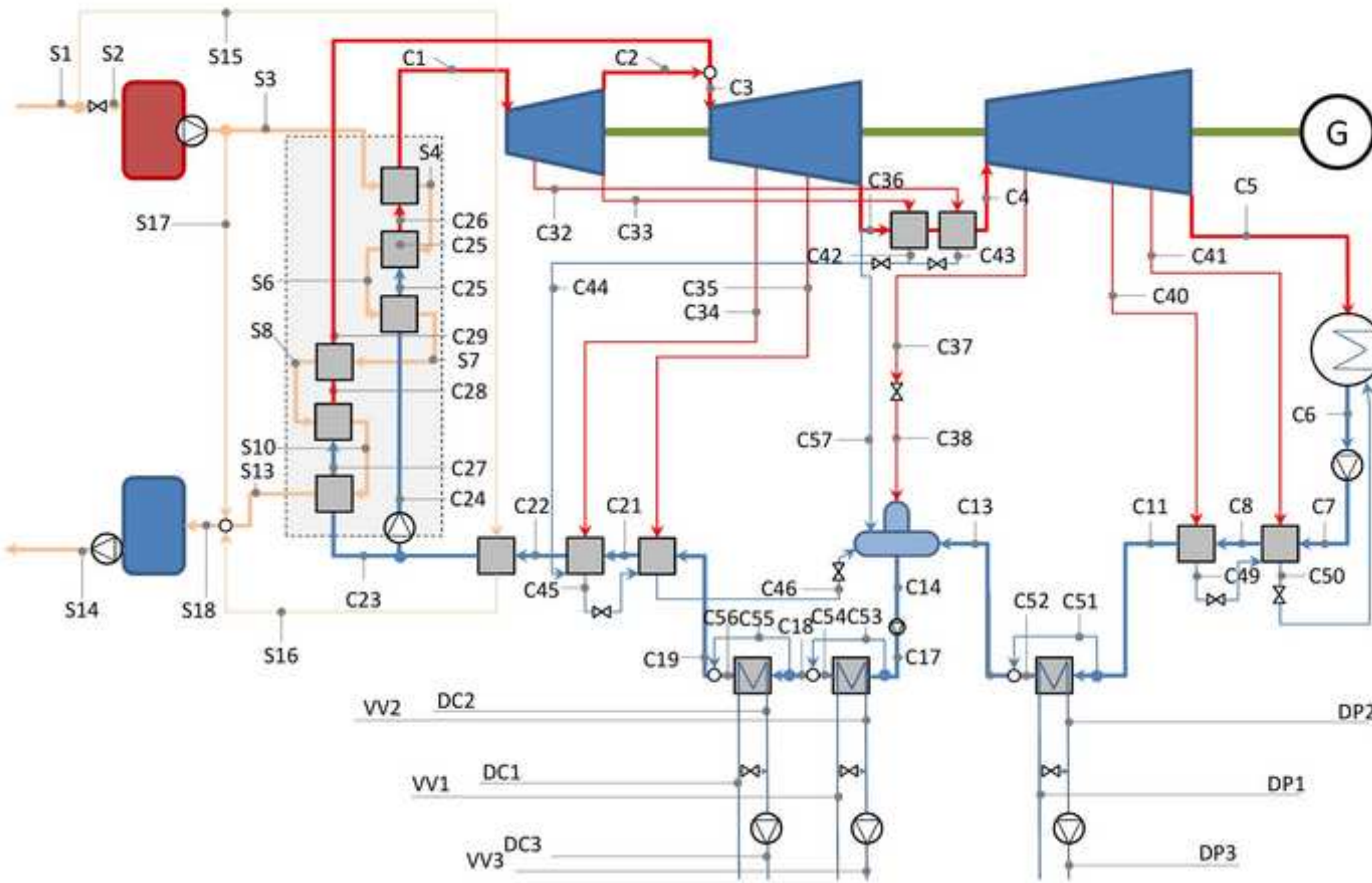

Figure 2

Click here to download high resolution image

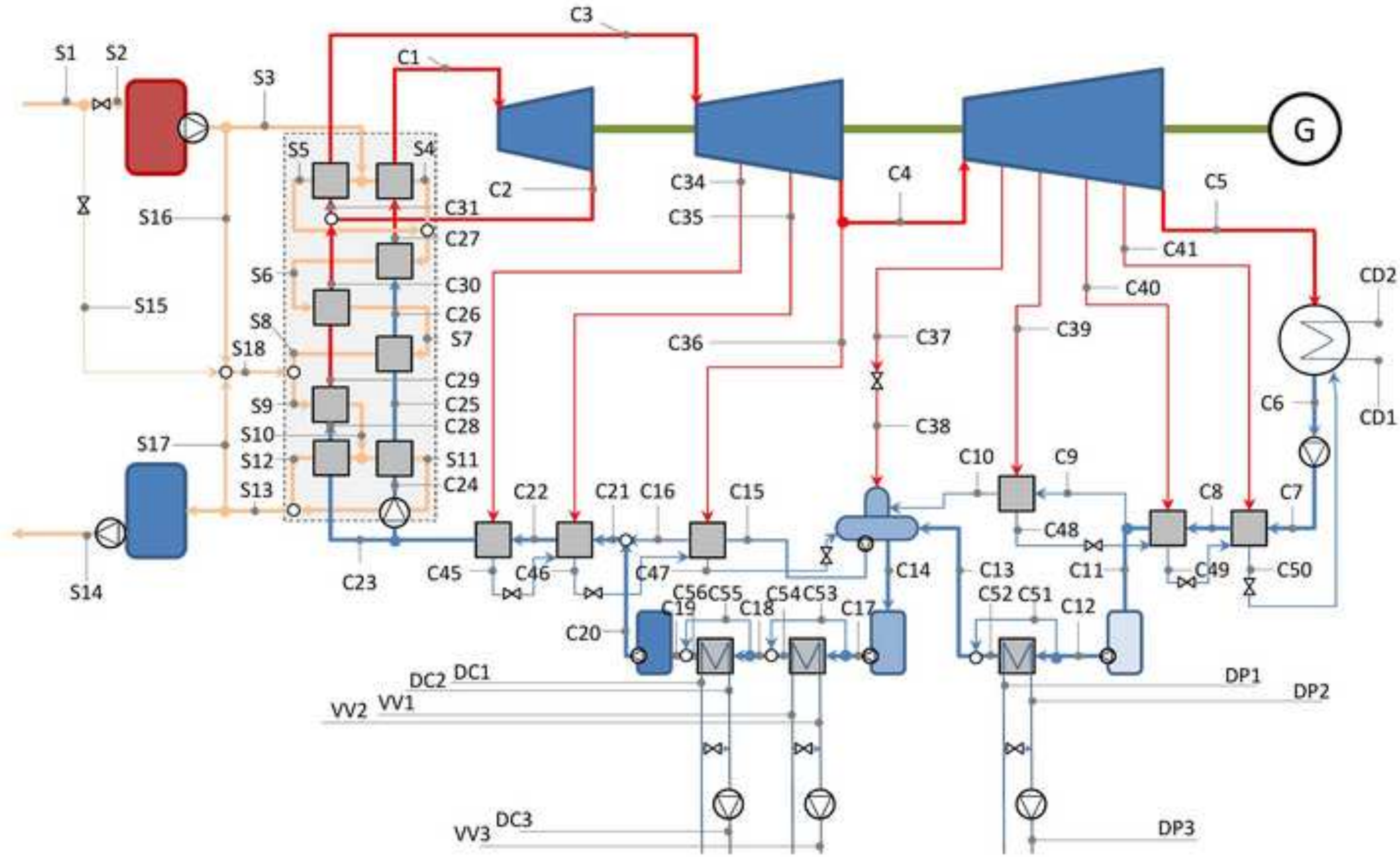

Figure 3
Click here to download high resolution image