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On the thermal dynamic behaviour of the helium-cooled DEMO fusion reactor

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Abstract. The EU-DEMO conceptual design is being conducted among research institutions and universities from 26 countries of European Union, Switzerland and Ukraine. Its mission is to realise electricity from nuclear fusion reaction by 2050. As DEMO has been conceived to deliver net electricity to the grid, the choice of the Breeding Blanket (BB) coolant plays a pivotal role in the reactor design having a strong influence on plant operation, safety and maintenance. In particular, due to the pulsed nature of the heat source, the Primary Heat Transfer System (PHTS) becomes a very important actor of the Balance of Plant (BoP) together with the Power Conversion System (PCS). Moreover, aiming to mitigate the potential negative impact of plasma pulsing on BoP equipment, for the DEMO plant is also being investigated a “heat transfer chain” option which envisages an Intermediate Heat Transfer System (IHTS) equipped with an Energy Storage System (ESS) between PHTS and PCS. Within this framework, a preliminary study has been carried out to analyse the thermal dynamic behaviour of the IHTS system for the Helium-Cooled Pebble Bed (HCPB) BB concept during pulse/dwell transition which should be still considered as the normal operating mode of a fusion power plant. Starting from preliminary thermal-hydraulic calculations made in order to size the main BoP components, the global performances of DEMO BoP have been quantitatively assessed focusing the attention on the attitude of the whole IHTS to smooth the sudden power variations which come from the plasma. The paper describes criteria and rationale followed to develop a numerical model which manages to simulate simple transient scenarios of DEMO BoP. Results of numerical simulations are presented and critically discussed in order to point out the main issues that DEMO BoP has to overcome to achieve a viable electricity power output.

1. Introduction

The EU-DEMO conceptual design is being conducted among research institutions and universities from 26 countries of European Union, Switzerland and Ukraine. Its mission is to realize electricity from nuclear fusion reaction by 2050. The recent European roadmap, has established that several hundred MW of electricity must be produced by DEMO plant which has to ensure an adequate availability and reliability of operation over a reasonable time span [1][2]. Due to this reason the EU-DEMO plant design has to be strongly oriented to the Balance of Plant (BoP).

The BoP in fact is made up of all those systems which scope is to convert the fusion power into electricity, the electrical power supply (that in a fusion facility is very huge), the cryogenic plant and several auxiliaries providing specific fluids and gases to the various apparatus according to their need [3].

The systems that are the core of the DEMO BoP, since they represent the fundamental energy “chain”, being devoted to the extraction of the plasma generated thermal power and to its conversion into electricity delivered to the grid, are the Primary Heat Transfer Systems (PHTSs) of Breeding Blanket (BB), Divertor (Div) and Vacuum Vessel (VV) and the Power Conversion System (PCS). The former are in charge of extracting the thermal power generated by the tokamak and delivering it to the latter in order to be converted first in mechanical and then into electrical power by means of the turbine and the alternator, respectively.

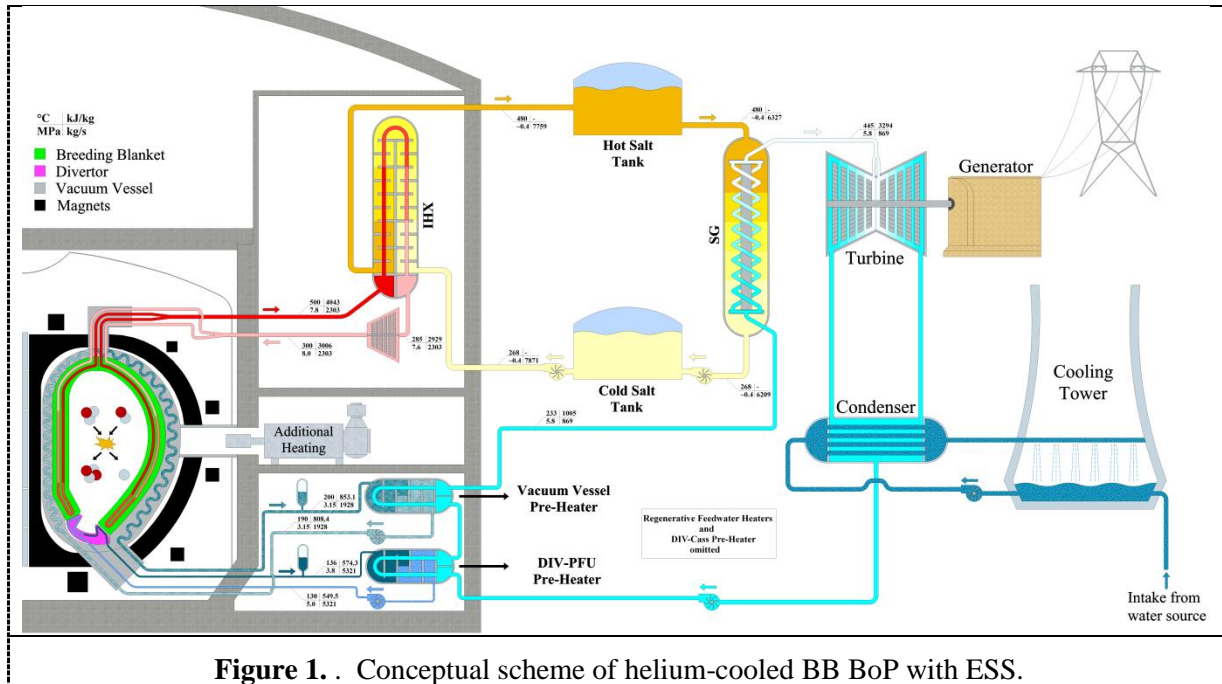
Such feature is a distinguish trait of a fusion power plant if compared to many fission Nuclear Power Plants (NPPs) where traditionally the BoP corresponds to the PCS only. In DEMO, indeed, the pulsed nature of the heat sources increase the dependence of PCS operation on the PHTSs making them the central actors of the BoP. However, this DEMO pulsed operation may lead to unacceptable fatigue stress on essential PCS components, therefore it is being developed a “heat transfer chain” configuration which foresees a third coolant system aimed at mitigating the potential negative impact of plasma pulsing on the turbine and the PCS equipment: the Intermediate Heat Transfer System (IHTS) that should decouple the BB PHTS to the PCS [3][4][5]. The IHTS is equipped with an Energy Storage System (ESS) that, during the pulse operation, collects a portion of the thermal energy removed from the blanket in order to give it to the PCS during the dwell time; in this way the turbine is allowed to work in steady-state condition both during the pulse and the dwell time of the tokamak.

It has been chosen to connect the IHTS only to the BB because it has to extract about 85% of the power generated by the tokamak, hence it might be intended as the main hub of the heat transfer chain. Another element that makes the DEMO BoP design more complex respect to other power plants is the presence of separated PHTSs. Such choice is necessary because the three main components that extract the thermal power from the machine - BB, Div and VV - have different functions and requirements making almost impossible the use of a single coolant operating at the same thermal-hydraulic (T/H) conditions. It is agreed that water will be used for the Div and VV cooling, while the selection of the BB coolants is still open; four blanket options are, in fact, under developments [6], nevertheless the DEMO BoP activities are currently focused on the two concepts whose feasibility seems achievable in shorter term: the Helium Cooled Pebble Bed (HCPB) and the Water Cooled Lithium Lead (WCLL) BB [5][7].

Within this framework, a preliminary study has been carried out to analyse the thermal dynamic behaviour of the IHTS for the HCPB BB concept during pulse/dwell transition which should be still considered as the normal operating mode of DEMO power plant. Starting from preliminary thermal-hydraulic calculations carried out to size the main BoP components, the global performances of DEMO BoP have been quantitatively assessed focusing the attention on the attitude of the whole IHTS to smooth the sudden variations of the plasma generated power. The paper describes criteria and rationale followed to develop a numerical model which manages to simulate simple transient scenarios of DEMO IHTS.

2. The HCPB BB BoP

The DEMO HCPB BoP is depicted in figure 1, where the main systems for the heat transport and power conversion are outlined, namely: the PHTSs, the IHTS with the ESS and the PCS which integrates the low temperature sources of Div and VV as feedwater pre-heaters.



2.1. PHTSs

DEMO presents four independent PHTSs. The bigger PHTS is devoted to the power removal from the BB, two PHTSs are necessary to extract heat from the Div while the last PHTS is used to cool the VV. Table 1 summarises the main parameters of DEMO PHTSs.

Table 1. DEMO PHTSs main data.

	BB	DIV-PFCs	DIV-Cass	VV
Coolant	Helium	Water	Water	Water
Thermal Power (Pulse/Dwell)[MW]	2389.1/21.4	136.0/1.4	115.2/1.1	86/1.0
Inlet temperature (Pulse) [°C]	300	130	180	190
Outlet temperature (Pulse) [°C]	500	136	210	200
Operating Pressure [MPa]	8	5	3.5	3.15

2.1.1. BB PHTS. The DEMO blanket is subdivided in 18 sectors, each one of 20°. Each sector includes two main zones, the Inboard Blanket (IB) and the Outboard Blanket (OB). These two areas are, in turn, subdivided in two sub-components, namely the First-Wall (FW) and the Breeding Zone (BZ): the FW has to withstand the plasma heat radiation and the additional heat loads due to impacting particles while the BZ contains lithium that is used as breeder material to produce tritium by means of nuclear reactions. FW and BZ are cooled in series by helium. The BB PHTS foresees a highly degree of segmentation of its cooling loops which are 9. These circuits are completely independent, from mechanical and functional point of view, in order to limit some common mode failures. In particular, there are 3 loops which are designed to cool the IB portion of the tokamak while the other 6 loops are in charge of removing the power from the OB zone. One IB cooling circuit provides helium to 6 blanket sectors while an OB loop cools the segments of 3 blanket sectors. Each IB/OB loop has 3 main parallel hot/cold legs, one Intermediate Heat eXchanger (IHx) and a couple of circulators which allow helium to circulate along the whole circuit [3][4].

2.1.2. *Div PHTS*. Divertor is primarily a high heat flux component. As for the blanket it is subdivided in 18 sectors of 20°. Div is separated in Plasma-Facing Components (PFCs), which represent the Div targets where are collected most of the particles and the energy exhausted by the plasma, and the Cassettes (Cass) that act as support for the PFCs. Both sections of Div are cooled by water but at different T/H conditions and by means of two separated cooling circuits. Each circuit is constituted of two loops which are directly coupled to the PCS via the heat exchanger that works as feed-water preheater [3].

2.1.3. *VV PHTS*. The Vacuum Vessel is a torus-shaped double-walled pressure vessel that provides the primary vacuum (at very low pressure and at very high purity in order to optimize the D-T fusion reaction) and shields the magnet system from neutrons. The VV supports all the in-vessel components including BB and Div. Also the VV is made up of 18 sectors and its cooling is provided by two independent circuits that give their contribution in the feed-water heating [3].

2.2. *IHTS*

The pulsed nature of the currently considered DEMO operation imposes unique design problems on the energy conversion system. In DEMO, energy is generated in the reactor for 120 minutes (pulse time) then the reactor is shut down for 30 minutes (dwell time) to recharge the central solenoid and to allow the vacuum inside the plasma chamber to be restored. However, several studies are on-going aimed at improving central solenoid recharge time and vacuum pumps performances in order to achieve a shorter dwell time which should last about 10 minutes [8]. During the dwell time the BB thermal power sharply drops to almost 1% of the nominal power due to the residual decay heat.

Since the PCS requires stable thermal operating conditions throughout the plasma operational phases, the IHTS equipped with an ESS, where a molten salt is used as heat transfer and storage medium, is being included in the BoP with the aim to mitigate the impact of plasma pulsing on main components, with particular care of steam turbine, Steam Generators (SGs), and the electrical grid.

The ESS of the DEMO is an industrial 2-tanks design commonly used in Concentrated Solar Power (CSP) plants [9]. The adoption of an ESS, in which part of the thermal power removed by molten salt in the IHXs is accumulated as sensible heat in dedicated tanks, allows to operate the PCS SGs at almost continuous load equal to about the 81% of the BB PHTS power, in fact its main mission is to avoid undue thermal and mechanical cycling on the main PCS components. However, since the energies of Div and VV are not stored, to furtherly limit thermal transients inside the PCS caused by the DEMO pulsed operations, the feed-water heat-up strategy foresees variable steam extractions from turbine and by-pass lines for Div and VV heat exchangers thus allowing continuous plant operations and flexibility in the range of turbine power scale of $\pm 20\%$. [9].

After a proper literature review of the molten salts technology [10][11], it has been decided to use the HITEC salt [12] as heat transfer fluid because its good thermal stability within the range of DEMO operative temperatures and its relatively low freezing point which gives more margins to withstand normal and off-normal transients. Table 2 summarises the operating condition of molten salt.

Table 2. IHTS molten salt operating condition.

Coolant	HITEC
Hot tank temperature [°C]	480
Cold tank temperature [°C]	268
Pressure [MPa]	0.1

2.3. *PCS*

The preliminary conceptual design of PCS for DEMO envisages a classical superheated steam Rankine cycle with SG, Reheater (RH) - in between high and low pressure turbine stages heated by

using a stream of hot molten salt -, Deaerator, Condenser and feed-water Pre-Heaters (PHs), operating at about 58 bar with superheated steam at 445°C [5].

Feed-water PHs are of condensing type or single phase fluid in both tube and shell side. In particular, the latter are represented by the heat exchangers of Div and VV PHTSs which are integrated in PCS as additional (low temperature) heat sources to improve system efficiency [3][9].

3. Preliminary sizing and thermal behaviour of IHTS components

A preliminary assessment of sizes and performances for the main equipment of the IHTS has been carried out in order to identify potential technical feasibility issues. The attention has been then focused on the IHTS thermal dynamic behaviour during pulse/dwell transition and on its attitude to smooth pulsed operations.

3.1. IHXs and SGs sizing

The thermal-hydraulic design of the IHXs has been performed starting from the basic methods commonly adopted to this purpose. The study has been focused on the “tubes and shell” heat exchanger technology for both the IHXs and the SGs. In particular, the former foreseen a typical straight tube bundle while for the SGs a helical coiled tube bundle layout has been selected. These configurations have been chosen in order to adopt components easily available on the market since they have been widely used in nuclear and conventional industrial applications for several decades.

3.1.1. Working fluids. The main properties of Helium and HITEC have been extracted respectively from [13] and [12], while as regard as water, its properties have been estimated according to IAPWS-97 functions [14]. Table 3 reports Helium and HITEC properties functions used in design calculations.

Table 2. Helium and HITEC properties.

Coolant	Helium (T in [K] and p in [bar])	HITEC (T in [°C])
Specific heat [J/(kg*K)]	5187.6	1560.0
Density [kg/m³]	$48.14 \frac{p}{T} \left[1 + 0.4446 \frac{p}{T^{1.2}} \right]^{-1}$	$2080 - 0.7324T$
Conductivity [W/(m*K)]	$2.682 \cdot 10^{-3} (1 + 1.123 \cdot 10^{-3} p) T^{(0.71(1-2 \cdot 10^{-4} p))}$	$e^{\{-3.8661 - 2.3903[\ln(T) - 4.8892]\}}$
Viscosity [Pa*s]	$3.674 \cdot 10^{-7} T^{0.7}$	$0.4465 + 0.1788 \cdot 10^{-3} T - 1.1486T^2$

3.1.2. IHXs. A two-pass tubes, two-pass shell configuration has been selected (TEMA NFN type) [15] to design this component which has been sized to withstand the thermal load that occurs during the pulse time. It has been also decided to let helium circulate through the tube bundle while HITEC salt flows on the shell side. Such choice has been made mainly due to the helium higher pressure and to mitigate potential LOCA effects. The tube side T/H conditions have been selected to be compliant with the BB PHTS requirements, in fact it has been taken into account the helium temperature at the IHX outlet that reaches about 285°C before helium is compressed by the circulators reporting its temperature at the BB target value of 300 °C. Moreover, the huge pumping power needed to circulate the coolant –177 MW for the whole BB PHTS - has been also considered in the IHXs design thermal inputs [4]. Therefore, the IHX T/H performances have been numerically investigated in detail by means of in-house developed code based on the log-mean temperature difference method [16]. In particular, the tube side heat transfer model of this tool relies on the use of the widely accepted correlation by Gnielinski [17] refined by correction factor which considers the influence of surface roughness on heat transfer as suggested by Shah and Bhatti in [18]; on the shell side, instead, to take into account the effects of various leakage and bypass streams on heat transfer coefficient and pressure drop, the Bell-Delaware procedure has been followed as discussed by Taborek in [16]. The main data of IHXs are shown in Table 3.

Table 3. IHTs main data

Parameter	IB IHX	OB IHX
Thermal Power [MW]	245.2	304.9
T_{in}/T_{out} helium [°C]	500.0/284.5	500.0/285.6
T_{in}/T_{out} HITEC salt [°C]	268.0/480.0	268.0/480.0
Tubes active length (per pass) [m]	17.0	16.5
Tube number (per pass) [-]	6779	8427
Tube external diameter [mm]	19.05	19.05
HITEC pressure drop [kPa]	163.4	156.1
HITEC volume [m³]	107.4	127.9

3.1.3. *SGs*. A helically coiled tube layout has been chosen to transfer the power from HITEC to water in order to produce superheated steam at about 450 °C. Due to its low operating pressure (close to atmospheric pressure), the molten salt flows downward outside the tubes, whereas the water/steam is circulated inside the pipe bundle upward generating a counter-current, cross-flow pattern. The T/H models and procedures applied to design the steam generator are mainly based on the Fenech's and Smith's methodologies [19][20] however more recent works [21][22] are also taken into account to characterise the different heat transfer regions of the water during its phase change, namely the liquid single-phase region, the subcooled boiling region, the saturated boiling region, the post-dryout region and the superheated steam single-phase region. As mentioned in sections 2.2., the power input of the SGs is about 81% of the heat transferred during the pulse at the IHXs and it has been evaluated considering compressors being run at nominal speed and constant power during both pulse and dwell periods and according the following formula (1):

$$\frac{\int_{pulse} (Q_{BB} + W_{Compr})dt + \int_{dwell} (Q_{BB} + W_{Compr})dt + \int_{ramp-up/down} (Q_{BB} + W_{Compr})dt}{(t_{pulse} + t_{dwell} + t_{ramp-up} + t_{ramp-down})} \quad (1)$$

where Q_{BB} and W_{Compr} are thermal and pumping power of the BB, respectively.

The resulted thermal power of 2092.3 MW is distributed among six Helical Coil Steam Generators (HCSGs) in order to limit the size of these equipment. The main parameters of the HCSG are reported in Table 4.

Table 4. HCSG main data

Parameter	Value
Thermal Power [MW]	348.7
T_{in}/T_{out} HITEC [°C]	480/268
T_{in}/T_{out} water [°C]	233/445
Tubes active length [m]	88.7
Tube number (per pass) [-]	885
Tube external diameter [mm]	22.225
HITEC pressure drop [kPa]	19.3
HITEC volume [m³]	35.7

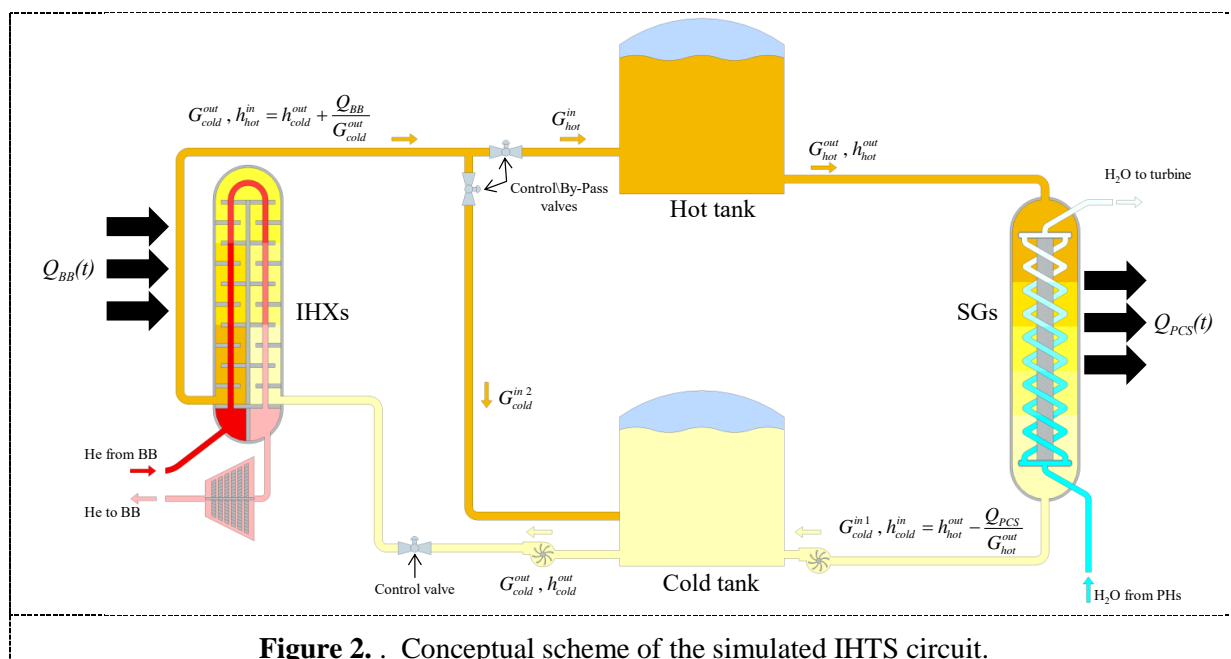
3.2. Storage tanks and IHTS thermal behaviour

Considering the requirement of a continuous PCS load, the characteristic time DEMO pulsation (e.g. pulse and dwell time) and the BB power, it follows that the minimum amount of energy that must be stored is about 950 MWh. Taking into account the properties of the HITEC salt and its temperature cycle, it derives the need of at least 10309 tons of fluid and thus tanks volume (hot + cold) of around

12000 m³. However, during the dwell period the energy source is no longer available at the maximum temperature due to the sharp drop of the BB power which implies a fast decrease of the helium temperature owing to the high volumetric flow displaced by the compressors. As consequence of the helium temperature reduction, the HITEC temperature at the IHXs outlet decreases too and, in cascade, the hot tank might be affected by this cooling effect making difficult the operation of the HCSGs as well as other PCS components. Such cooling process could be hypothetically avoided decreasing the mass flow rate of helium at about 1% of the nominal value operating on the compressor speed but such a huge difference from nominal condition in these heavy turbomachinery seems not to be easily achievable [23][24][25], moreover continuous and quick big changes of compressor angular velocity might decrease its qualified lifetime. For these reasons it has been preliminary chosen to keep the compressors at nominal speed assuming, as first approximation, no changes in power consumption, regardless from their inlet conditions. Feasibility studies on the design of variable speed compressors, working within speed range suitable for the main operative conditions of the BB PHTS, are currently under development with the involvement of industry [8].

$$\frac{dm}{dt} = \sum_i G_i^{in} - \sum_i G_i^{out} \quad (2)$$

Where m is the mass, G is the mass flow rate and h is the enthalpy.



As can be gathered from the figure 2, it has been assumed that, thanks to huge IHXs heat transfer area, the power generated in the BB is instantaneously transferred to the intermediate circuit even during the pulse/dwell transition, neglecting any potential delays due to the thermal inertia of the PHTS; this assumption relies on the fact that helium thermal inertia is several order of magnitude lower than the total one of the intermediate coolant hence the time to reach its asymptotic conditions is supposed to be quite shorter compared to that of the HITEC. On the PCS side, it has been postulated that this system must always work in (quasi) steady-state condition, therefore the molten salt mass flow rate flowing through the SGs is kept at nominal value in order to deliver a constant power to the water/steam; such assumption can be considered valid until the hot molten salt temperature does not differ too much from its nominal value allowing the SGs to operate properly, otherwise it is likely to fall into error. The pulse/dwell transition has been analysed for three different plasma ramp-up/down scenarios: the first is a borderline case where a sudden variation of the power from dwell to pulse is simulated by means of a step function, while the other two, representative of more realistic situations [27][28][29], consider a linear increase of the BB power from dwell to pulse values, lasting 100s and 200s, respectively; the ramp-down is treated in specular way. In all three cases, during the dwell time, the molten salt charging flow (from cold tank to hot tank) is supposed to be ideally regulated in order to the average helium temperature at 400°C, by using control and by-pass valves as well as decreasing the pump speed. These preliminary studies have been performed starting with the minimum amount of HITEC stored into the tanks. Then, a sensitivity analysis has been performed with the aim of evaluating the suitable inventory of molten salt which should be stored to avoid huge variations in the coolant temperatures. Table 5 shows the main input parameter adopted in the developed transients.

Table 5. Transients input data.

Cases	$Q_{BB \text{ Pulse}}/Q_{BB \text{ Dwell}}$ [MW]	Q_{PCS} [MW]	t_{Pulse}/t_{Dwell} [s]	$t_{Ramp-up}/t_{Ramp-down}$ [s]	Initial mass stored [t]
Case 1	2566.1/198.4	2092.6	7200/1800	0/0	10309
Case 2	2566.1/198.4	2077.1	7200/1800	100/100	10676
Case 3	2566.1/198.4	2062.4	7200/1800	200/200	11032

3.2.2. Results. The time “0” of each simulation have been properly chosen in order to reach the beginning of the dwell period after 2 hours of the transient. Figure 3 shows the mass flow rate distributions in the main heat transfer equipment of the IHTS circuit, namely the IHXs and the SGs, and in the by-pass duct which allows the HITEC coming from the IHXs to be recirculated toward the cold tank during dwell and ramp-up/down times. Such operation is necessary to achieve a complete balance of the masses between the two storage tanks. The molten salt mass flow rate in IHXs and SGs have been calculated to be compliant with the input and output powers of the system. As can be observed in figures 4, 5 and 6, the calculated profiles of temperature in the main IHTS components show very common trends for all three scenarios. However, when dwell time is running out, disagreements can be recognised in the temperatures of hot tank and, as effect, at the SGs outlet. This can be ascribed to the different mass inventory presents in the hot tank throughout the final phases of the dwell. In particular, it could be noted that the sharper is the pulse/dwell transition, the lower is the quantity of salt remained in hot reservoir at the end of dwell, finding as extreme situation the one related to the Case 1 where the tank gets empty just before the beginning of the pulse and the HITEC temperature drop to the same value reached at the SGs outlet. With regard to the Case 1, it is evident that the assumption of providing constant power to the PCS becomes very shaky since it is hard to think that SGs can keep the same heat transfer performances when the temperature of its power source decreases of more than 60°C. Cases 2 and 3 are less affected to temperature reduction because the mass of HITEC which is in the hot tank at the end of dwell – 225 and 443 tons, respectively – provides a thermal inertia sufficient to avoid a dramatic temperature drop maintaining it within 20° C. Nevertheless, operating continuously the SGs inside this temperature window might intensify the ageing of the components caused by a pronounced thermal fatigue [30].

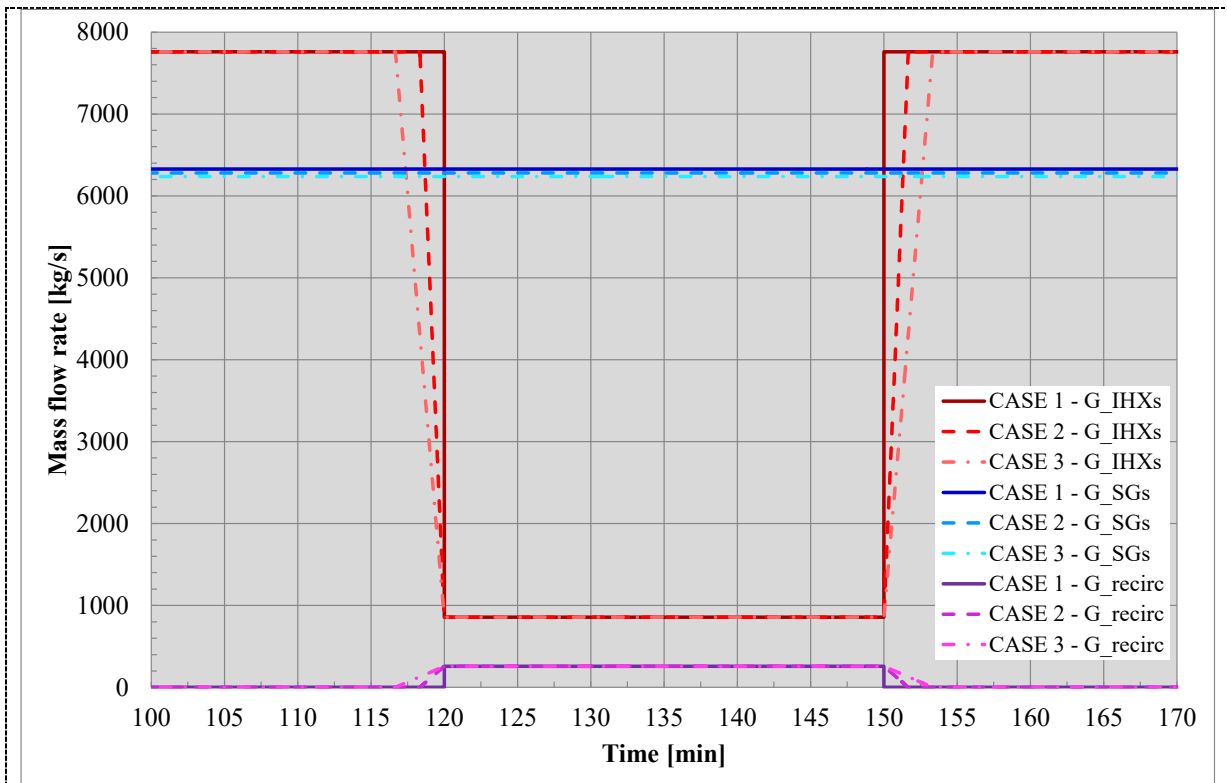


Figure 3. Mass flow rates distribution in IHXs, SGs and by-pass duct.

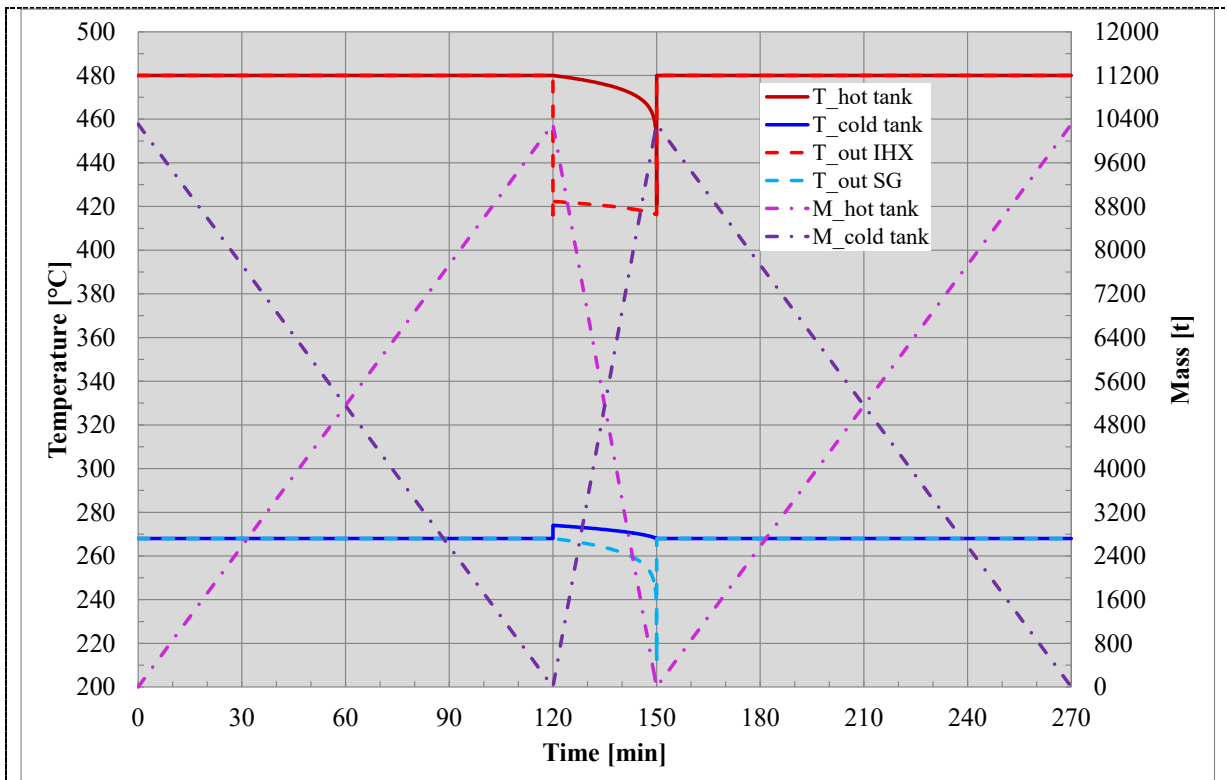


Figure 4. CASE 1 - Main IHTS temperature profiles and mass inventory of hot and cold tanks.

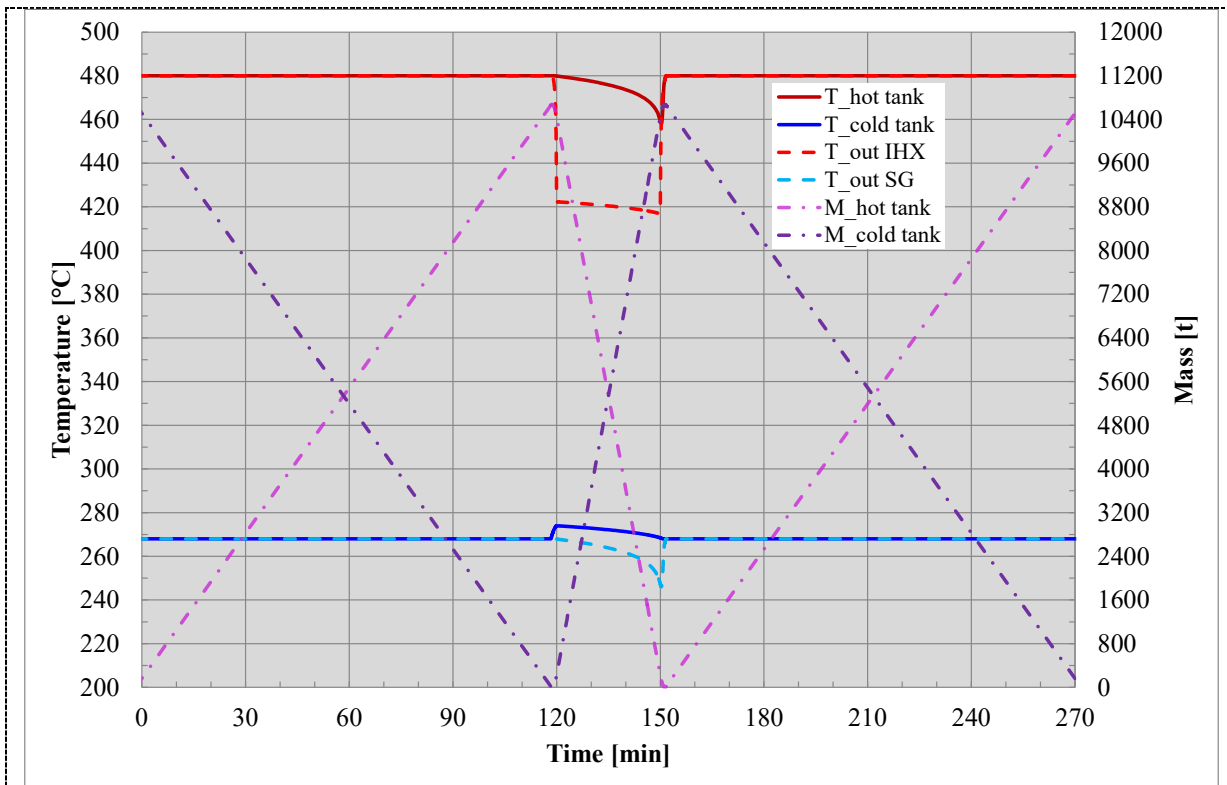


Figure 5. CASE 2 - Main IHTS temperature profiles and mass inventory of hot and cold tanks.

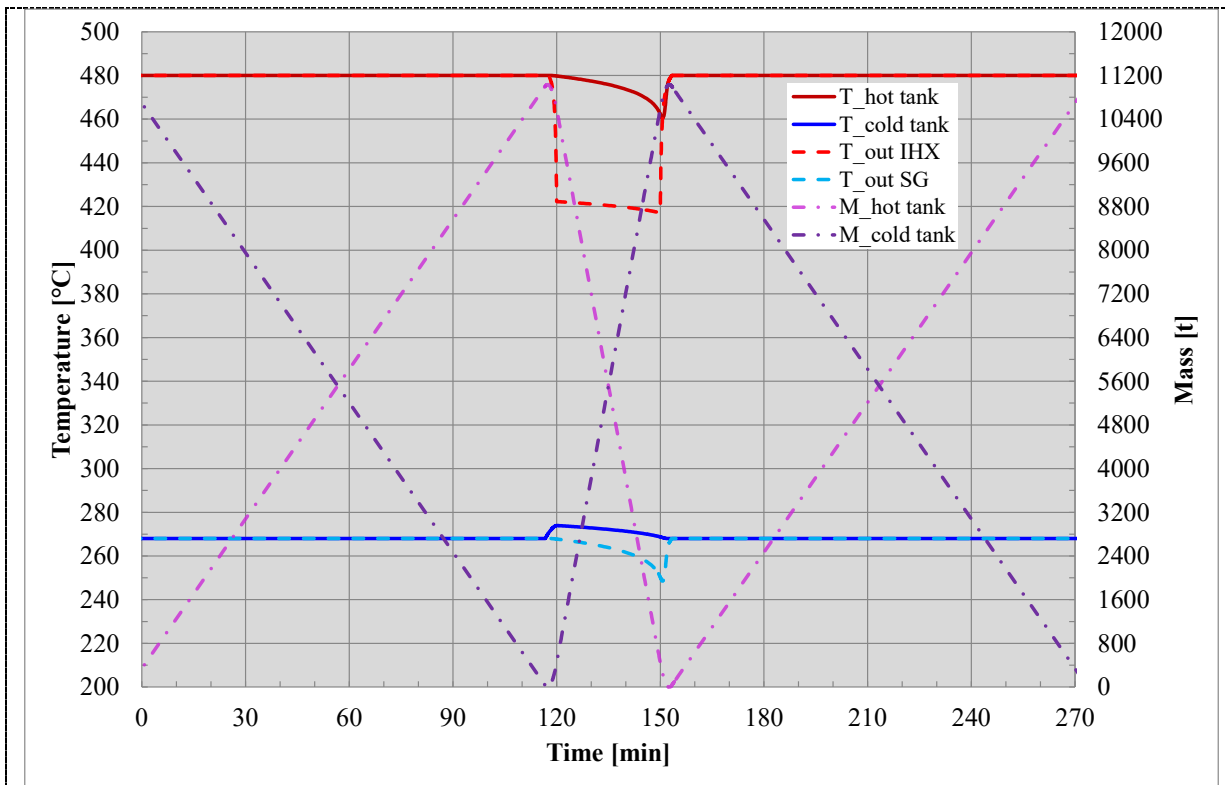


Figure 6. CASE 3 - Main IHTS temperature profiles and mass inventory of hot and cold tanks.

For the abovementioned reasons, starting from the previous cases, further analyses have been performed increasing the quantity of stored molten salt with the aim of finding the amount of HITEC which should be foreseen to keep the temperature variations in a range of 5°C. To obtain this objective it has been finally estimated that the molten salt mass should be augmented of about 75% respect to the minimum hypothetical value. Figure 7 reports the evolution of the coolant bulk temperatures during the pulse/dwell transition inside both hot and cold tank and at the IHXs outlet. Each group of three curves is referred to the Case 1#, Case 2# and Case 3# which differ from the earlier scenarios owing to the initial salt inventory that, as said, has been increased of 75%.

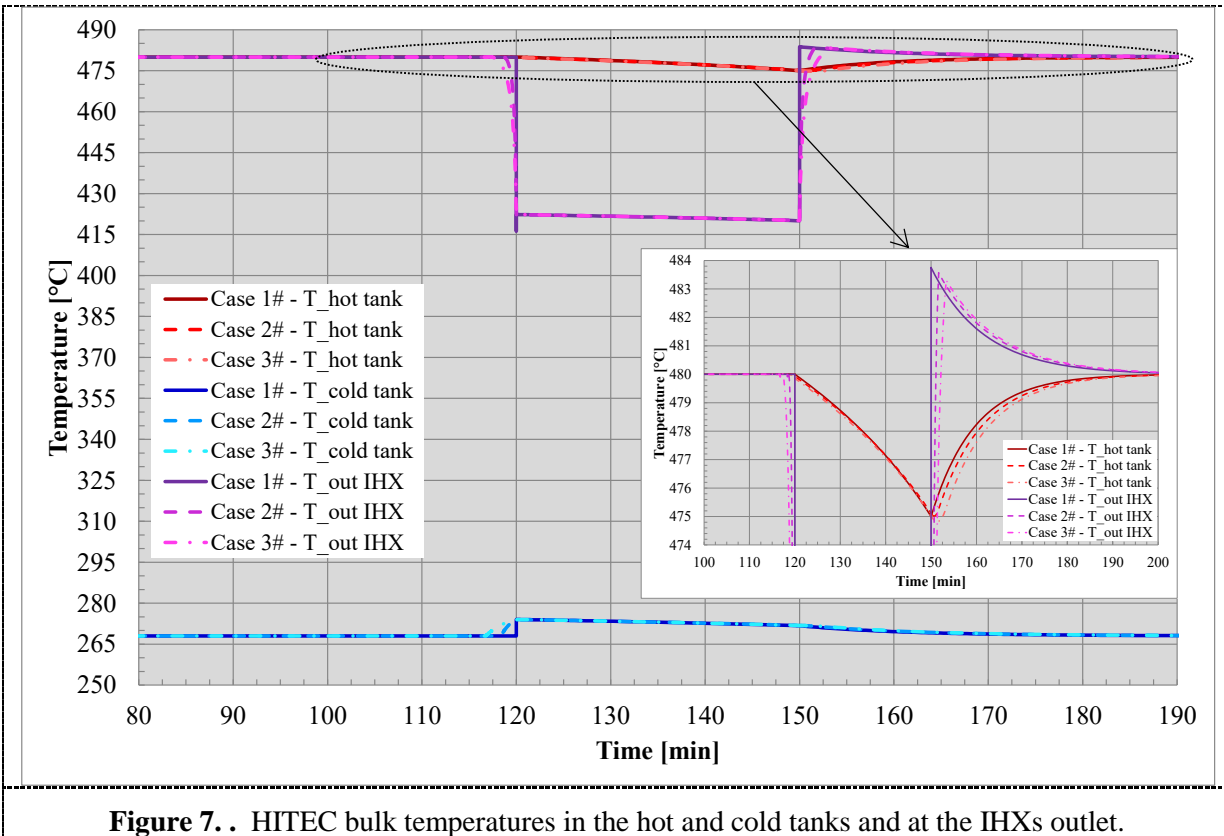


Figure 7. HITEC bulk temperatures in the hot and cold tanks and at the IHXs outlet.

4. Conclusion

A preliminary assessment of the main component sizes of the IHTS and its connected ESS for the HCPB BB concept of the DEMO fusion power plant has been carried out. The conceptual design of the main components belonging these systems have been developed focusing the attention on equipment configurations widely used in nuclear and conventional industrial applications. In particular, the choice of the “tube and shell” architecture for the design of the heat exchangers has been mainly driven by the degree of maturity that such type of layout offers as well as by its relatively simple design which usually shows great flexibility to meet almost any service requirement. The results have highlighted that the overall dimensions of these components are huge however their size and design T/H are still comparable to those which can be commonly found in SGs of many NPPs. Mechanical design and verification are on-going to confirm the viability of the solution. Further refinements of the heat exchangers design are on-going dealt to optimize their heat transfer area by using different tube bundle layouts and/or increasing the temperature difference between coolants. Thermal dynamic analyses on the IHTS has been also performed to study the global behaviour of the system during pulse/dwell transition and its attitude to smooth the sudden power variations which

come from the plasma. A theoretical model based on a lumped parameter approach has been set-up to assess the evolution of both mass inventory and fluid bulk temperature in the hot and cold tanks during the main operation phases of DEMO. According to the hypotheses and the simplification made, results have shown that storing the minimum amount of molten salt could be not sufficient to reach a stable PCS operation since, in all cases analysed, the coolant is experienced by moderate to high reductions of temperature at the SGs inlet during the final stages of the dwell time. Therefore further parametric studies have been carried out to estimate the mass needed to be stored into the two ESS tanks in order to keep the temperature variations of the HITEC in a range of 5°C. It has been found that, for the given input data, to pursue such goal about 18000 tons of molten salt would be necessary. Additional analyses will be performed in the future to study the effects caused by: 1) a reduction of the dwell time from 30 to 10 minutes, 2) different BB PHTS temperature control strategies, 3) different BB PHTS compressor control strategies.

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