Dynamic simulations of the cryogenic system of a tokamak

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Abstract. Power generation in the next decades could be provided by thermo-nuclear fusion reactors like tokamaks. There inside, the fusion reaction takes place thanks to the generation of plasmas at hundreds of millions of degrees that must be confined magnetically with superconductive coils, cooled down to 4.4K. The plasma works cyclically and the coil system is subjected to pulsed heat load which has to be handled by the refrigerator. By smoothing the variable loads, the refrigerator capacity can be set close to the average power; optimizing investment and operational costs. Within the “Broader Approach agreement” related to ITER project, CEA (Commissariat à l’Energie Atomique et aux Energies Alternatives) is in charge of providing the cryogenic system for the Japanese tokamak (JT-60SA), that is currently under construction in Naka. The system has been designed to handle the pulsed heat loads. To prepare the acceptance tests of the cryogenic system foreseen in 2016, both dynamic modelling and experimental tests on a scaled down mock-up are of high interest for assessing pulsed load smoothing control. After explaining HELIOS (HElium Loop for hIgh lOad Smoothing) operating modes, a dynamic model is presented, with results on the pulsed heat load scenarios. All the simulations have been performed with EcosimPro® and the associated cryogenic library CRYOLIB.

1. Introduction

The main goal of thermonuclear fusion devices is to confine a dense plasma sufficiently long to use the released fusion power into electrical power. An example of such an experimental device is the tokamak JT-60SA which is currently under construction in Naka, at JAEA’s Fusion Institute (Ibaraki prefecture, Japan). JT-60SA (Japan Torus - 60 Super Advanced tokamak) construction is part of the Broader Approach to the ITER project. CEA is in charge of providing the cryogenic system for this experimental device among other European contributions.

Tokamak operation requires several superconductive coils working cyclically, meaning that those magnets are facing a variable heat load. In order to reduce and optimize the investment cost, there is the need of smoothing the peak of the pulse, hence the refrigerator size can be reduced accordingly. To better describe how this smoothing strategy impacts the reactor operation, we focus on the “Auxiliary Cold Box” (hereafter referred as ACB), the helium distribution cold box connecting the magnet loops with the Refrigerator Cold Box (RCB).

There are two distinct parts: primary circuit, namely the loop, in which the coolant is flowing through a cold circulating pump, and the secondary circuit which contains the buffer capacity where the pulse energy is stored and gradually released during a period of idle operation. The coolant is supercritical helium while the thermal buffer capacity is a saturated liquid helium bath (nominally 4.2K, 1 bar).

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The two circuits are thermally coupled by two heat exchangers allowing the heat coming from the loop and from the circulator to be removed by the thermal buffer. The pressure inside this thermal buffer is allowed to fluctuate to maintain a constant vapor mass-flow back to the refrigerator. Such a procedure was already tested at CEA-SBT (CEA-Service des Basses Températures) using a 1:20 scale down mockup of the JT-60SA magnet cryogenic system [1].

The JT-60SA refrigerator is currently being assembled on site and will be tested before its connection to the magnets. For testing the cryogenic system, a loop by-pass circuit is included inside the ACB. In order to prepare the acceptance tests [2], the existing HELIOS facility has been modified accordingly (volumes associated with magnets have been removed and replaced by the scale down volume of the by-pass line). Furthermore, previous modelling using EcosimPro code together with CRYOLIB library [3] of the HELIOS Facility have been updated with this new configuration. The goal is to investigate how a pulsed heat load scenario is handled by the ACB equipped with the by-pass circuit with no coils connected yet.

In order to be able to compare experimental data with dynamic simulation outputs we worked on a scaled down mock-up of the JT-60SA cryogenic system ACB. Several tests have been performed on the new set-up of HELIOS in order to investigate which transients will take place during the acceptance tests. According to JT-60SA technical specifications, the test is passed if the cryogenic provides the requested cooling capacity during the pulsed load scenarios [2]. In other words pressure, temperature and mass-flow in the loop are bounded as follows:

- Mass-flow in the loop $\geq 48g/s$
- Pump pressure head $\geq 0.8$ bar
- Loop temperature at the inlet of the heating line $4.4K \leq T \leq 4.8K$

To simulate the cyclical behavior of the tokamak, a portion of the ACB piping has been heated with a pulsed profile described in figure 1 which lasts 3600s to simulate two subsequent pulses. The peak of the pulse is at 245W which represents 1/20th of the pulse peak injected in JT-60SA’s ACB.

![Figure 1. Profile of the pulsed heat load applied on HELIOS during the experimental tests.](image)

2. The experimental set-up
HELIOS has been assembled on the actual geometry of JT-60SA ACB ([2]), this means that the capacity of the thermal buffer, containing saturated liquid helium, is 340 liters and there are 12 liters of SHe flowing in the loop. Hence, we are dealing with an experimental set-up where the volume, the mass-flow and the power have been scaled down to 1:20 with respect to the acceptance test conditions. Since the fluid properties are the same than in the real tokamak, the transit time is the same and hence, we can reproduce on HELIOS the same thermal-hydraulic transients which are supposed to take place on JT-60SA’s ACB. HELIOS represents only loop 2 of the ACB corresponding to the distribution lines to the CS (Central Solenoid) and EF (Equilibrium Field) magnets, an additional heater has been added to the bath to simulate the variable heat input by the TF (Toroidal Field) coils and structures. (Figure 2).
3. Operating modes, Controls, Configurations

HELIOS can work either keeping the helium inventory constant (Isochoric mode) or keeping constant the pressure in the loop (Isobaric mode) by managing supply and removal of fluid.

Figure 3. HELIOS, isochoric configuration, constant helium inventory in the loop. CV941/949 are closed.

Figure 4. HELIOS, isobaric configuration, the pressure PT955 is regulated through CV941 and CV949.

The main difference in between the two modes (isochoric and isobaric) relies in opening or not the control valves CV941 and CV949. In both configurations several controls can be implemented. The bath outlet mass-flow FE969 is always controlled via the opening of the control valve CV969. At the same time, a PID (Proportional Integral Derivative) controller regulates the bath level or the bath inlet mass-flow via the opening of the control valve CV940. The control on the bath level is active until steady state is achieved, then the heat pulse is launched and the control is switched to the bath inlet mass-flow, the actuator remaining the control valve CV940. It is possible to add a further control on the mass flow in the loop by varying the speed of the pump.

Both isochoric and isobaric configurations have been modelled using EcosimPro.
Initial conditions (Table 1) mainly concern the helium inventory. Initial pressure and temperatures along the loop fix the mass inside the loop itself and the pressure at steady state before pulses are launched. Initial temperature and bath level fix the mass inside the bath. Boundary conditions are there to account for the heat loads and controls. The dynamic model calculates the time dependent temperature distribution over the loop as well as the pressure and the position of the actuators used in the implemented controls.

**Table 1. Model input. (All pressures are absolute pressures.)**

| INITIAL CONDITIONS          |               |
|-----------------------------|---------------|
| Loop                        | 4.4 K , 5.7 bar |
| Bath                        | 4.3 K , 71 % liquid level |
| High Pressure Line – HP     | 4.7 K , 6 bar |
| Low Pressure Line – LP      | 4.3 K , 1.16 bar |

| BOUNDARY CONDITIONS         |               |
|-----------------------------|---------------|
| Bath mass flow control      | 16.2 g/s inlet – FE940 |
|                             | 19.0 g/s outlet – FE969 |
| Loop fixed settings         | 3.4 W (Estimated Static Losses) |
| Time dependent power applied to the loop | |

| IF Isobaric Configuration   | 5 bar – PT950 (constant pressure in the loop) |
| IF Mass Flow Control Active | FE955 = 48 g/s (constant mass flow in the loop) |

The heatig line has been modified [1] to take into account the bypass line only. It has been modelled using a series of one dimensional pipes, component which incorporate mass, energy and momentum conservation equations in transient operation so that transition time is well simulated along the loop. The pump has been coded ad hoc to reproduce the actual Barber-Nichols cold circulator installed on HELIOS. The bath is a 0D reservoir created in order to be equipped with two heat exchangers.

### 3.1. Isochoric configuration

This is the reference configuration for the acceptance tests of JT-60SA. The helium inventory in the loop is kept constant, control valves CV941/CV949 are closed. The heat of the pulse is stored in the bath that shows a peak increase in the pressure of around +0.25 bar.

![Figure 5. Bath pressure, each peak corresponds to one pulse, the rising amplitude is 0.25 bar. On the secondary axis, the heat load profile.](image)

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![Figure 6. Bath outlet mass-flow control, via CV969. On the secondary axis, the heat load profile.](image)

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Other important information, which can be drawn from Figure 5, is that the dwell time between pulses is enough to recover the initial condition before launching the second pulse. The bath outlet control is very well reproduced by the simulation (Figure 6). The massflow in the loop is 49g/s (Figure 8) and
the pressure head across the circulating pump is about 0.815 bar (Figure 7). The simulation seems to slightly underestimate (of about 5 mbar) the loss of pressure head across the pump.

When the pulse occurs, the pressure drops increase in the circuit, which tends to decrease the mass flow. However, this effect is overcompensated by the increase in density due to the increase of the pressure inside the loop.

![Figure 7](image7.png)  
**Figure 7.** Pump pressure head, above the minimum requirement of 0.8 bar. On the secondary axis, the heat load profile.

![Figure 8](image8.png)  
**Figure 8.** Mass-flow in the loop, above the minimum requirement of 48 g/s. On the secondary axis, the heat load profile.

The temperature at the inlet of the heated sector, Figure 9, is quite well reproduced; the discrepancy in this case is about 20 mK within the measurement uncertainty. This temperature measurement is quite important since it is one of the parameter monitored during the acceptance test and it represents the interface with the magnets. There is some margin left when comparing this temperature to the limit given in the technical specifications, hence it can be relaxed during dwell time up to 4.8 K. Hence, the inlet loop temperature, mass flow and pump pressure head fulfill the criteria required for the acceptance test. This proves that the acceptance tests in isochoric configuration should be feasible.

![Figure 9](image9.png)  
**Figure 9.** Temperature at the inlet of the heating sector. On the secondary axis, the heat load profile.

![Figure 10](image10.png)  
**Figure 10.** Temperature at the outlet of the heating sector. On the secondary axis, the heat load profile.

The same temperature (Figure 9) reproduces the saturation temperature of the bath plus the increment due to the thermal gradient through the heat exchanger and static losses due to radiation. The peak of the bath pressure (Figure 5) is 1.42 bar, it corresponds to 4.6 K. The heat exchanger is responsible for 50 mK of the temperature rise which yields to 4.65 K. The peak in the experience curve in Figure 9 reaches 4.7 K meaning that there is a further rise in temperature (50 mK) accountable to radiation losses.
At the outlet of the heated sector, Figure 10, simulation and experimental curves almost juxtaposed, since here, the increase is almost due to the applied heat load only, hence radiation losses are very marginal in this portion of the circuit.

To complete the picture of this first but referential case, Figure 11 shows the loop pressure increase compared to the steady state. The small discrepancy in between experimental and simulated values can be explained with an overall underestimation of the static heat losses in the loop.

3.2. Isobaric configuration, focus on the mass flow control

Although the isochoric configuration is the reference case, both HELIOS and JT-60SA can also work under isobaric conditions. This means that the two control valves CV941 and CV949 regulate in order to keep the pressure constant.

If necessary, it is possible to use the pump to keep the mass flow in the loop constant as well, by acting on the pump speed. If in the isochoric case mass-flow oscillations will account for ±0.6 g/s variation only, in the hardest case (figure 6), this pump speed control can be useful in the current isobaric configuration where the flow presents around 2 g/s oscillations (figure 12).

This fluctuation in the mass flow is due to a compensation in the density which is lacking under isobaric regime whilst it takes place indeed under isochoric. The isochoric configuration implies a pressurization of the line which yields to a rise in the helium density compensated by the thermal heating process.

On the other hand, in isobaric mode, the increase in pressure loss is not compensated by the increase of density at the pump inlet so mass flow rate tends to decrease when heat load is applied.
Figure 13. Isobaric configuration: mass-flow in the loop (left) and the speed of the circulating pump (right). The mass flow is controlled by varying the pump speed. On the secondary axis, the heat load profile.

This test highlights a very important aspect, which could be challenging at the time of JT-60SA commissioning. If there are up to 2 g/s oscillations in the isobaric configuration, it is important to set the mass flow in the loop high enough not to lower below 48 g/s during the transient otherwise the acceptance test will be failed. Moreover, the test with the pump mass flow control showed how useful this actuator can be to avoid a decrease of the mass flow during the pulse.

3.3. Comparing Isochoric and Isobaric configuration, both with the mass flow control activated

For both configurations, the mass flow in the loop is controlled by the circulating pump at 48 g/s. The experimental bath pressure peak in isobaric is about 50 mbar higher compared to the isochoric value (Figure 14-b). Same trend for the temperature at the inlet of the heating sector (Figure 14-a), there are 50 mK difference in between the isobaric and isochoric scenario. Comparing with the simulation curves, there is a good accordance in the isochoric scenario while there is a small discrepancy in between the isobaric ones. Figure 14-a shows an offset in the initial conditions between isochoric and isobaric mode. Configurations are not strictly identical; the pressure in the loop in the case of isochoric operation was 5.7 bar, whilst the pressure value in the isobaric case was kept constant at 5 bar. This explains why the experimental isobaric curve is lower than the isochoric one before the pulse is applied.

Concerning the bath pressure, (14-b), the difference in the peak pressure can be explained with an isobaric configuration loop which has additional heat losses, compared to the isochoric one, due to the added circuits associated with the pressure control. This results in a longer mass flow control which yields to higher pressure peak in the bath. These circuits represent the lines in which the actuators (CV949-941) are installed. Additional static heat losses associated to this added circuits have not been introduced in the model yet, this explains why isobaric numerical curves are lower than the respective experimental ones.

The outlet heating temperature (14-c) is slightly underestimated by the simulation in the isochoric, due to the underestimation of the heat losses. This case is different from Figure 10, here the pump velocity is varying, reaching the maximum corresponding to the heat peak, there are consequently some more Watts injected in the circuit (due to the increase of friction loss). The isobaric mode reaches a lower peak in temperature: at constant pressure of 5 bar, the helium heat capacity is higher compared to helium at 6-7 bar in isochoric regime.

All these considerations are summarized in in the variation of the outlet mass flow of the bath (Figure 14-d) where on the final part of the transient the shortest time control corresponds to the isochoric simulation followed by the isochoric experiment, the isobaric simulation and the isobaric experiment.
Figure 14. Comparing Isochoric and Isobaric configurations; the heating sector inlet temperature [a]; the bath pressure [b]; the heating sector outlet temperature [c] and the bath outlet control [d].

4. Comments and Conclusions
Generally speaking the results obtained with the experimental campaign performed on HELIOS were quantitatively and qualitatively well reproduced, by the model. This gives confidence that extrapolation of the model to the complete ACB will give reasonable predictions for the acceptance tests on JT-60SA refrigerator. Both operation modes for the magnet cooling loop were simulated and tested (isochoric and isobaric configurations) and the results show that the two operations are possible with the easiest operation for isochoric which is now considered as the nominal operation for JT-60SA ACB loops. All the discrepancies in the curves have been understood and explained leading to a better knowledge of the process.

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