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Dynamic thermal-hydraulic simulations of the JT-60SA cryogenic system for preparing plasma operation

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Abstract. Recent measurements on the JT-60SA toroidal field coils showed a slightly higher pressure drop than expected, resulting in a lower supercritical helium mass flow rate during normal plasma operation. This paper presents some simulations of the cooling loop considering these updated thermal-hydraulic parameters and the expected pulsed heat loads. The model includes a cold circulator, heat exchangers, helium thermal buffer, the distribution system and the superconducting coils. The article presents the differences between the initial scenario which was validated during commissioning of the cryogenic system and the updated scenario to prepare plasma operation with the cryo-magnetic system. The simulation also provides the transient heat load profiles of the cooling loop, highlighting a first smoothing of the thermal loads at the interface with the cryogenic system. The Simcryogenics code, developed at CEA Grenoble, is used to simulate the dynamic loads.

1. Introduction
The JT-60SA superconducting tokamak is a joint European-Japanese fusion project, presently under assembly in Naka, Japan [1]. The superconducting magnets are cooled by supercritical helium loops and designed for the peaked heat loads during plasma operation. The cryogenic system is a French voluntary contribution within the Broader Approach and was commissioned in 2016 [1]. As the tokamak is still being assembled, the performance of the cryogenic system was demonstrated during the acceptance tests with pulsed loads by test heaters. The heat load profiles were derived from dynamic thermal hydraulic simulations using Vincenta (a thermal hydraulics simulation code) and analytical calculations [2]. Two supercritical helium loops are driven by cold circulators: loop 1 is dedicated to the toroidal field coils (TF) and the structures while loop 2 is dedicated to the central solenoid and equilibrium field coils. The paper presents additional thermal-hydraulic modelling results, focusing on the toroidal field coils and the structures. Indeed measurements on the JT-60SA TF coils during manufacturing phase [3] and during cryogenic tests showed some slightly higher pressure drop (+10-15%) compared to the design value of 1.1 bar for a nominal mass flow of 4 g/s in each single–channel cable in conduit conductor (CICC) of the 18 TF coils. Based on previous thermal hydraulic results, it has been
agreed that a reduced mass flow of 3g/s might be acceptable to keep a safe temperature margin for the conductor with respect to the current sharing temperature. Beside the cold circulator remains in its operating range, avoiding an increase of its pressure head. Complementary dynamic simulations with the thermal-hydraulic code Simcryogenics developed by CEA [4], have been performed to estimate the impact of this reduced mass flow on the heat load profiles at the interface with the refrigerator. The paper is organized as follows: section 2 presents the model used in this study, while section 3 compares the results with those obtained previously with Vincenta. Section 4 presents some predictions obtained with the Simcryogenics software for a reduced mass flow rate through the TF conductors. Finally, section 5 gives the conclusions and the perspective for future studies.

2. Model presentation

The loop 1 of JT-60SA has been simulated with the Simcryogenics software. Each segment of supply & return lines, TF CICCs, TF and CS structures have been modelled by 1 dimensional pipes. Fig. 1 presents the overall schematic of the model. The two heat exchangers HX1 and HX2 immersed in the 4.4 K buffer bath extract the heat loads from the TF coils and the structures and from the cold circulator C1. The details of the block containing the lines _TF_01_06_CSstr_7_9_TFstr_13_18 are shown in Fig. 2. The TF CICC is modelled by the component TF, while the structures are modelled with the TF_str and the CS_str components. The thermal-hydraulics channels which are in parallel and equivalent are modelled only once, and the resulting flowrate is multiplied by the number of parallel channels, indicated below by the component with a cross in Fig. 1 and 2.

2.1. TF coils and TF and CS structure description

The main characteristics of the TF CICCs, TF and CS structures are listed in Table 1. To benchmark the two softwares, a particular attention has been taken by setting the same parameters for the simulations. On both models, a heat transfer coefficient between the CICCs and the helium has been chosen to be 25 \( \text{W/m}^2\cdot \text{K} \), while a coefficient of 750 \( \text{W/m}^2\cdot \text{K} \) has been chosen between the TF or CS structures and the helium flow.

2.2. Heat loads

The heat loads applied to the TF CICC (nuclear heating, conductor losses) and the TF/CS structures (nuclear heating, eddy currents, radiative and conductive loads) can be found in [2] and the variable parts are presented in Fig. 3. In this study, the heat loads have been uniformly
Table 1: main characteristics of the TF CICC and TF and CS structures. *Re* stands for the Reynolds number while *Rr* depicts the pipe roughness (taken as 1.5e-4)

| Properties                  | TF CICCs       | TF Structures | CS Structures |
|-----------------------------|----------------|---------------|---------------|
| Number of it [1]            | 18 x 12        | 18 x 2        | 9 x 4         |
| Type                        | Nb-Ti + Cu     | stainless steel |              |
| Length [m]                  | 113            | 18.81         | 7.75          |
| Cross section [m²]          | 1.27e-4        | 1e-04         | 1.96e-05      |
| Mass [kg]                   | 5110           | 14500         | 32900         |
| Wetted perimeter [m]        | 1.111          | 0.04          | 0.0157        |
| Void Fraction [1]           | 0.32           | 1             | 1             |
| Heat exchange coef. [W/m²·K] | 25             | 750           | 750           |
| Friction factor [5]         | \(\frac{19.5 \times Re^{-0.79} + 0.023}{\text{void}^{0.742}}\) | 0.11 * (68/Re + Rr)^{0.25} | |

distributed along the pipe lengths. One can see that the heat load profiles are pulsed, especially during the plasma initialisation (the highest peak). A constant heat load of 270 W have been applied for the joints and 201 W have been applied as static losses along the cryodistribution pipes.

3. Comparison between Vincenta and Simcryogenics

A simulation of the reference scenario performed with Simcryogenics has been compared to the Vincenta’s results [2]. Fig. 4 shows a good agreement between the prediction results of the two 1D thermal hydraulic codes. The transit time along the loop is about 800 s which explains the smoothing effect of the peak heat loads on both the TF coils and structures when the loads are finally deposited in the 4.4 K bath. Simcryogenics could simulate again the same heat loads profile which was tested during commissioning test of the cryogenic system (Fig. 4 (g)). The computation time of the Simcryogenics model is approximately 10 minutes on an Intel i7 laptop.

4. Estimation of the heat load profile at the interface of the refrigerator with a reduced mass flow in the TF conductor

The model described in the previous section is used to predict the heat load profile to be extracted from the HX2 heat exchanger when the flowrate through the TF CICC is reduced from 4 g/s
Figure 3: Heat loads applied to the TF coils, the TF structures and the CS structures. The normalized time is the actual time divided by the cycle time (1800 s). The power is constant between the normalized time 0.2 and 1. The heat load deposited on the structures are truncated since the peak value are respectively 234.2 kW and 107.9 kW respectively for the TF and the CS structures for 0.13 s during start of the plasma.

Figure 4: Comparison of the results by Vincenta and Simcryogenics. a) inlet and outlet pressures at the inlet and the outlet of the cold circulator C1. b) inlet and outlet temperatures of the TF coils. c) inlet and outlet temperatures of the TF structures. d) inlet and outlet temperatures of CS structures. e) TF CICC inlet flowrate. f) heat exchanged through HX2. The normalized time stands for the actual time divided by the cycle time (1800 s).

to 3 g/s. The comparison between the two cases is shown in Fig. 5. One can see that the inlet and outlet temperature of the CICC is not higher in the 3 g/s configuration. The average heat load on the heat exchanger HX2 is slightly lower in the 3 g/s configuration (-0.1 kW), due to the Joule Thomson effect along the TF CICC. Indeed the expansion from 6 to 4.9 bar at 4.45 K warms up the helium flow, equivalent to a thermal load proportional to the mass flow. The heat load absorbed by the helium bath has a smoother profile for 3 g/s (Fig. 5 (b)), so less
demanding in terms of cooling supply by the cryogenic system as the maximum load is reduced from 2.5 to 2.25 kW.

![Comparison of results for 4 g/s and 3 g/s in the TF CICC (864 g/s and 648 g/s in total for loop 1).](image)

Figure 5: Comparison of the results for 4 g/s and 3 g/s in the TF CICC (864 g/s and 648 g/s in total for loop 1). a) inlet and outlet temperatures of the TF coils. b) heat exchanged through the HX2 (with average value). The normalized time stands for the actual time divided by the cycle time (1800 s).

5. Conclusions

The cryogenic engineering department of the CEA is developing the Simcryogenics library for MATLAB Simulink, that is used in numerous applications. In this study, a model of the loop 1 of the JT-60SA cryodistribution has been developed. It has been compared to previous results obtained with a Vincenta model, which were used for the test acceptance of the cryogenic system. Results show a good accordance of the two codes. This model requires less computation time (i.e. 10 minutes to obtain the results presented Fig. 5 against several hours) and more flexibility for parametric studies, will be used in the next future to predict the behavior of the loop 1 and particularly the heat deposited on the heat exchangers, with a reduction of the flowrate during the dwell time \( t = [170-1800] \) s for saving refrigeration power from the cold circulator. This tool will also be used to prepare the integrated commissioning phase: different heat loads profiles and their impacts on the cryogenic system operation will be investigated and could be validated with additional tests at cryogenic temperature before the connection with the superconducting magnets. Additional investigations on the controls for the pulsed load smoothing will be carried out with this model.

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