Model-based minimization algorithm of a supercritical helium loop consumption subject to operational constraints

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Abstract. Supercritical helium loops at 4.2 K are the baseline cooling strategy of tokamaks superconducting magnets (JT-60SA, ITER, DEMO, etc.). This loops work with cryogenic circulators that force a supercritical helium flow through the superconducting magnets in order that the temperature stay below the working range all along their length. This paper shows that a supercritical helium loop associated with a saturated liquid helium bath can satisfy temperature constraints in different ways (playing on bath temperature and on the supercritical flow), but that only one is optimal from an energy point of view (every Watt consumed at 4.2 K consumes at least 220 W of electrical power). To find the optimal operational conditions, an algorithm capable of minimizing an objective function (energy consumption at 5 bar, 5 K) subject to constraints has been written. This algorithm works with a supercritical loop model realized with the Simcryogenics [2] library. This article describes the model used and the results of constrained optimization. It will be possible to see that the changes in operating point on the temperature of the magnet (e.g. in case of a change in the plasma configuration) involves large changes on the cryodistribution optimal operating point. Recommendations will be made to ensure that the energetic consumption is kept as low as possible despite the changing operating point. This work is partially supported by EUROfusion Consortium through the Euratom Research and Training Program 2014-2018 under Grant 633053.

1. Introduction
Large superconducting tokamak or particle accelerator devices produce significant heat loads on their magnets, due to static losses, huge eddy currents encountered in the magnetic system, to AC losses and to neutron flux radiations. The cooling system must be able to cool the magnets, taking into account that the heat load can be very variable. It makes it necessary to create and use a specific optimization algorithm that will minimize the cryogenic power consumption despite the variable heat loads, taking into account operational constraints.

The forced flow supercritical helium cooling scheme is assumed to be the baseline solution for DEMO [5], as in ITER [1] and in JT-60SA [4]. A dedicated loop is driven by a cold circulator nominally at 4.5 K and 6 bar with a pressure drop of 1 bar. These are the assumptions in thermal-hydraulic analysis of the TF CICC [5]. The thermal loads on the magnets are extracted through heat exchangers into a saturated liquid helium bath supplied by a refrigerator cycle [3]. A model has been developed with the Simcryogenics library to simulate a TF loop in interface...
with a refrigerator. Its main purpose is to perform 0D or 1D thermal-hydraulic calculation on the cold part of the cryogenic system. It has been designed for parametric studies.

This paper is organized as follows. Section two presents the generic cryodistribution dynamical model made with the Simcryogenics library. Section three presents the operational constraints that apply to the model and the figure of merit to minimize associated to the energetic optimization (subject to constraints) results. Section 4 concludes the paper and gives ideas for future work.

This work is partially supported by EUROfusion Consortium through the Euratom Research and Training Program 20142018 under Grant 633053. The part of the task presented deals with the future DEMO cryogenic system.

2. Generic hydraulic cryodistribution scheme
Neither the cryo-distribution scheme nor the CICC properties has been defined at this stage of the DEMO project. That is why this paper propose to work on a generic cryodistribution scheme. This generic scheme allows us to work on the optimization algorithm where results are presented in the next section, and is also the baseline to develop flexible tool to optimize the design of the cryodistribution, to calculate the optimal operation conditions and make recommendations accordingly in a minimum amount of time. This section will first present the cryodistribution scheme that has been used to optimize the power consumption and the associated variables. The main assumptions on the circuit will be detailed and operational constraint will be enumerated.

2.1. Model
To study the optimal operating points for the cooling of the CICC magnet with supercritical helium, a hydraulic cryo-distribution model with one TF CICC with an associated heat load of 10 W is proposed. The modelling has been done with the Simcryogenics library under

![Diagram](image)

**Figure 1.** Simcryogenics model for the CICC cryodistribution optimization.
the MATLAB/Simulink/Simscape development environment [2]. Figure 1 presents the model schematic that has been used to search for optimal parameters.

The model presented in Figure 1 is composed of several valves (CV1, CV2 and CV3), a phase separator (PS1), a cold compressor (C1), a cold circulator (C2), two 0D pipes (pipe1 and pipe2), one pressure drop (PD1) and one heat load (HL1) that represents the CICC. The blue (grey in the b & w version) round items represent sources and sinks: it simulates the helium supply from the refrigerator. To stabilize the level of helium in the phase separator, there is a LC1 (level controller) controller working with the Joule-Thomson CV1 valve. To regulate the temperature in the bath, there is a TC1 (temperature controller) controller working with the cold compressor C1.

2.2. Variables
This section presents the variables appearing in Figure 1 and particularly the variables used afterwards. It will be classified by type.

- **Temperatures**
  - TT1: Inlet of the CICC, called \( T_m \) hereafter
  - TT2: Outlet of the CICC, called \( T_{out} \) hereafter
  - TT3: Outlet of the cold compressor C1

- **Pressures**
  - PT1: Inlet of the CICC, called \( P_m \) hereafter
  - PT2: Outlet of the CICC, called \( P_{out} \) hereafter
  - PT3: Outlet of the bath, called \( P_{bath} \) hereafter

- **enthalpy balance**
  - DHT1: Total cryogenic power consumption at 7 bar, 5 K
  - DHT2: Enthalpy flux difference between before and after the cold compressor C1
  - DHT3: Enthalpy flux difference between before and after the cold circulator C2

2.3. Assumptions
Many modelling assumptions has been made to build the Simcryogenics library and this particular model. They cannot be recalled here. This section will only presents the assumptions that are to be known to understand the following. More details about the software used for simulation can be found in [2].

**Cold compressor and cold circulator**: An isentropic efficiency of 65 % is assumed for the cold compressor C1 and the the cold circulator C2.

**Phase separator**: The outlet temperature of the phase separator heat exchangers is considered to be 0.05 K above the helium bath temperature. The helium bath temperature is considered homogeneous in the phase separator.

**Pressure loss**: The pressure loss induced by PL1 is considered to be driven by the following law: \( \Delta p = \Delta p_0 \cdot (M/M_0)\alpha \), where \( \Delta p \) represents the pressure drop, \( M \) the mass flow rate creating the pressure drop. In this paper, \( \Delta p_0 = 1 \) bar, \( M_0 = 12 \) g/s and \( \alpha = 2 \)
2.4. Objective function, optimization variable and operational constraints
As this article proposes to minimise the cryogenic power consumption, it must be defined. The power consumption will be considered to be equal to be $DHT_1$, being the enthalpy flux difference between the "P/T source" and the "P sink". To minimise it, we will use two optimization variables: the bath temperature $T_{bath}$ and the mass flowrate $M_{loop}$ in the CICC. Many constraints can be set and respected while the energetic cost is minimized. This paper will focus on the three that seems the most important: the inlet and outlet temperature $T_{in}$ and $T_{out}$ of the CICC (that must be kept under a maximum), as well as the bath pressure $P_{bath}$, that cannot be pumped down to 0 bar for obvious technological reasons. Now that the objective function, the optimization variable and the operational constraints have been defined, the results of such optimization will be presented.

3. Optimization
Before detailing the optimization results, we will show that the optimization step is important through a figure showing the energy consumption of the system. In the following, notations $T_{out}$, $T_{in}$ and $P_{bath}$ will be used to describe the constraint on the original variable.

3.1. Necessity
To show that it is necessary to optimize the power consumption with $M_{loop}$ (the flowrate in the loop) and $T_{bath}$ (the bath temperature) variable, the power consumption $DHT_1$ is plotted as a function of $T_{bath}$ subject to the $T_{out} \leq T_{out}$ constraint. This plot is presented in Figure 2.

![Figure 2](image_url)

**Figure 2.** Cryogenic power consumption (a) and associated flowrate (b) $M_{loop}$ as a function a $T_{bath}$ for different maximal $T_{out}$.

Figure 2 shows that for each constraint on the output temperature $T_{out}$ (4.5 K, 4.75 K, 5 K), there is a different $(M_{loop}, T_{bath})$ couple that give the minimum cryogenic power consumption. The fact that the optimal $(M_{loop}, T_{bath})$ is changing with the operating point must be taken into account to design the cryosystems of DEMO. Components (cold circulator, cold compressors,...) must be chosen to be able to follow the excursion of $(M_{loop}, T_{bath})$ optimal parameters since they vary in the case where the maximal $T_{out}$ condition is varying (e.g. if the plasma condition is changing, the $T_{out}$ condition may also change). To generate Figure 2, a vector of $T_{bath}$ has
been defined and the flowrate $M_{\text{loop}}$ that ensure that the constraint on the maximal value of $T_{\text{out}}$ is respected has been calculated for each element of the $T_{\text{bath}}$ vector. This is a good way to plot figures but it takes too much time to get the results. This is why an appropriate algorithm that will search for the optimal couple $(M_{\text{loop}}, T_{\text{bath}})$ that minimize the cryogenic consumption subject to the $T_{\text{out}} < T_{\text{out}}^{\text{max}}$ constraint will be used.

3.2. Optimization results

This optimization will be performed first with one only constraint: the output temperature of the CICC will be kept under a maximum. Formerly, this problem can be wrote:

$$
\mathcal{P}(M_{\text{loop}}, T_{\text{bath}}) = \left\{ \min \ DHT1 \quad \text{s.t.} \quad T_{\text{out}} \leq T_{\text{out}}^{\text{max}} \right\}
$$

In which $\mathcal{P}$ is the problem to solve, $DHT1$ the cryogenic power consumption, $T_{\text{out}}$ the output temperature of the CICC and $T_{\text{out}}^{\text{max}}$ the maximum admissible outlet temperature of the CICC.

Again for illustration purposes, this algorithm has been run for $T_{\text{out}} = 4 K$, meaning that the actual $T_{\text{out}}$ at the end of the optimization sequence must be lower or equal to $4 K$. Figure 3 shows the optimization variable and the optimization objectives as a function of the iteration of the optimization algorithm.

Figure 3. Algorithm execution for $T_{\text{out}} = 4 K$. It converged to the minimum cryogenic power after 10 iterations, respecting the constraint.

Figure 3 shows that in a few iterations that take minutes, the optimization variable $(M_{\text{loop}}, T_{\text{bath}})$ that minimize the operation cost and respect the constraint is set. This algorithm
can be run for any load on the loop or any constraint on $T_{out}$. To illustrate its capabilities, it has been run for a vector of $T_{out}$ constraints. The result on the cryogenic power consumption and on the optimization variables it plotted in Figure 4.

![Graph showing flowrate, pressure, temperature, and power consumption as a function of constraint on $T_{out}$](image)

**Figure 4.** Optimal $(M_{loop}, T_{bath})$ couple that minimize the power consumption as a function of the $T_{out}$ constraint.

Figure 4 shows that the lower the constraint on the output temperature is, the higher the cryogenics power consumption. It also shows that the two optimization variables $(M_{loop}, T_{bath})$ has to be driven together in order to be at the minimum cryogenic consumption if the $T_{out}$ condition is changing. Such an algorithm is essential because without it, the cryogenic power consumption will always been suboptimal, leading to energy waste.

This algorithm can be run for any constraints to minimize any criteria which can be a sum of criteria. The next section presents the same results than this section, but with additional constraints.

### 3.3. Optimization with additional constraints

For technological reasons, one could want to set other constraints related to the cryodistribution scheme. For instance, the cryogenic energetic cost can be minimized while the input temperature of the CICC is constrained to be below a maximum, or the bath pressure can be constrained to be above a minimum. Figure 5 presents such an optimization problem. Formally, the optimization
problem that has been solved is written:

\[
P \in (M_{\text{loop}}, T_{\text{bath}}) = \begin{cases} 
\min : & DHT_1 \\
\text{s.t.} : & T_{\text{out}} \leq \overline{T}_{\text{out}} \\
& T_{\text{in}} \leq \overline{T}_{\text{in}} \\
& P_{\text{bath}} \geq P_{\text{bath}}\end{cases}
\]

(2)

where in this case, \( P_{\text{bath}} \) has been choose to be 0.125 bar and \( \overline{T}_{\text{in}} \) is equal to 4 K. Figure 5 presents the results of such and optimization problem.

![Figure 5](image)

**Figure 5.** Optimization results with additional inlet temperature and bath pressure constraint. The optimization algorithm has been run again to solve the \( P_2 \) (in red) problem for a vector of \( T_{\text{out}} \) from 3.25 K to 5 K, subject to the additional constraint \( P_{\text{bath}} = 0.125 \) bar and \( \overline{T}_{\text{in}} = 4 \) K.

One can see in Figure 5 that the additional constraints that have been set are respected. Obviously, when constraints are active (i.e. \( T_{\text{in}} = \overline{T}_{\text{in}} \) and/or \( P_{\text{bath}} = P_{\text{bath}} \), the minimum power consumption is increasing regarding the unconstrained case (i.e. \( T_{\text{in}} \) and \( P_{\text{bath}} \) free).

4. Conclusion

A model capable to simulate a simplified cryodistribution system to keep a CICC cold has been built. It shows that in order to satisfy operational constraints, there is an infinite number of solutions in terms of CICC flowrate and/or bath temperature, but that only one (bath temperature/ CICC mass flowrate) is optimal from an energy point of view. This model/algorithm also shows that if constraints change (regarding the plasma condition for example), the cryoplant to come must be designed to pursue the optimal operating point, in
order not to waste energy. This model can be completed with other components to be more relevant regarding the real installation. Operational or technological constraints can also be set if needed.

In the future, this algorithm will be used to see if some supercritical cryodistribution scheme built in the past for tokamaks could have been improved with such an algorithm. We will also be focused on building an algorithm capable of real-time operation, to calculate the optimal set points to be given to the process controller, in order to pursue to optimal operating point, leading to real-time energy savings.

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