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Heat load estimator for smoothing pulsed heat loads on supercritical helium loops

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Abstract

Superconducting magnets for fusion are subjected to large variations of heat loads due to cycling operation of tokamaks. The cryogenic system shall operate smoothly to extract the pulsed heat loads by circulating supercritical helium into the coils and structures. However the value of the total heat loads and its temporal variation are not known before the plasma scenario starts. A real-time heat load estimator is of interest for the process control of the cryogenic system in order to anticipate the arrival of pulsed heat loads to the refrigerator and finally to optimize the operation of the cryogenic system. The large variation of the thermal loads affects the physical parameters of the supercritical helium loop (pressure, temperature, mass flow) so those signals can be used for calculating instantaneously the loads deposited into the loop. The methodology and algorithm are addressed in the article for estimating the heat load deposition before it reaches the refrigerator. The CEA patented process control has been implemented in a Programmable Logic Controller (PLC) and has been successfully validated on the HELIOS test facility at CEA Grenoble.

This heat load estimator is complementary to pulsed load smoothing strategies providing an estimation of the optimized refrigeration power. It can also effectively improve the process control during the transient between different operating modes by adjusting the refrigeration power to the need. This way, the heat load estimator participates to the safe operation of the cryogenic system.

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Keywords: refrigeration power, pulsed heat load smothing, supercritical helium

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1. Introduction

Tokamaks in operation such as KSTAR, or future devices (JT-60SA and ITER) are nuclear fusion reactors where the plasma is confined and controlled with high magnetics fields. The high magnetic field is generated thanks to superconducting magnets. These magnets are cooled with forced flow supercritical helium at 4.4 K and 0.5 MPa. The cooling loop is driven by a circulating pump (c. 1) and extracts the heat loads of the magnets through heat exchangers to a saturated helium bath. The helium bath is supplied by the refrigerator, the cold source production.

In tokamaks, plasma operation induces cyclic and pulsed heat loads on the magnets due to nuclear reactions, eddy currents in the structures and AC losses in the coils. Hence the refrigerator has to handle variable heat loads and shall adapt its refrigeration power: during the plasma phase the loads to extract are maximum, whereas during the dwell (Fig. 2), the refrigeration power can be reduced. However the refrigerator is usually designed for stationary loads and dedicated controls and regulations can be developed to optimize its operating range. Heat load strategies have been investigated on a scaled down experiment HELIOS at CEA-SBT [1], and also with dynamic modeling codes: 4C [2], EcosimPro [3,4]. In these studies, the refrigerator operates at the average loads and different controls on the return mass flow to the refrigerator (thermal buffer, cold circulator, by-pass valve) show the effective mitigations of pulsed heat loads at the interface with the refrigerator. Other works and propositions from refrigerator manufacturer ALAT [5] have focussed the mitigations of pulsed loads on the refrigerator's side, controlling the parameters of cycle pressure and/or mass flow rate. In these pulsed load smoothing methods, the heat loads from the magnets have to be estimated to adapt the refrigerator power to the need. In real plasma operation, the heat loads to the magnets are not known, neither its profile versus time. The paper presents a heat load estimator which relies on the evaluation of the heat loads before they reach the saturated helium bath. It takes advantage of the helium volume of the cooling loop between the superconducting magnets and the heat exchanger HX2 (Fig. 1), which drive the heat transport time. The heat loads are estimated using the physical measurements on the cooling loop: pressure, temperature and mass flow. This estimation can be calculated before the loads affect the refrigerator and hence the controls and regulations can be efficiently anticipated. After a description of the method of the patented process [6] and its algorithm, an experimental validation is presented on the HELIOS test facility. An application to a heat load smoothing strategy is also given and opens the discussions to other possible applications.

Nomenclature

ρ	density (kg.m^{-1})
V	volume (m3)
u	specific internal energy (J.kg^{-1})
h	specific internal enthalpy (J.kg^{-1})
$\dot{q}$	heat load (W)
$\dot{m}$	mass flow (kg.s^{-1})
P	pressure (Pa)
T	temperature (K)
x	vapour fraction (-)
L_{sat}	latent heat of vaporization (J.kg^{-1})
T_0	cycle period time (s)

2. Description of the methodology and algorithm

2.1. Heat loads to a cooling circuit

The heat load estimator calculates in real time the thermal loads which are deposited into the loop from the superconducting magnets, before they are transferred to the saturated helium bath (Fig. 1). The methodology can be summarized in three steps (Fig. 2):

- The PLC interpolates helium properties such as specific enthalpy, specific internal energy and density using Hepak [7] with linear functions from 2D tables stored into the memory system, using the sensor measurements (pressure, temperature).
- Variation of the energy in the loop is estimated with an energy balance of the system (geometry and helium inventory are known) and the heat thermal load deposited into the loop can be deduced.
- The thermal heat load estimation can be used as an input in the pulsed load strategy in order to optimize the control and regulation of the refrigeration power.

The control is active all along the cycle, with variation of the set points according to the heat load estimation. The set points can be calculated for the mass flows to/from the refrigerator. The values will be increased to cope with an increase of the estimated thermal loads, whereas the values will be reduced if the estimated thermal loads decrease. At t1, the pulse is over, the total energy is deposited into the loop and will affect the refrigerator after the transport time to the liquid helium bath. The heat load estimator enables to anticipate the maximum refrigeration power.

2.2. Energy balance and heat load estimator

The heat load estimator can be either applied on an isochoric loop (closed loop with constant helium inventory into the loop) or on an isobaric loop (open loop with pressure regulation with a supply line through V2 and discharge line through V3).

In isochoric loop, the variation of the pressure is directly coupled to its energy variation and hence to the deposited heat loads. In isobaric loop, the pressure is regulated so the charging and discharging mass flows are the main drivers of the energy fluxes of the loop. The internal energy balance in the loop can be derived as follows:

$$\rho V \frac{du}{dt} + \frac{d\rho}{dt} V u = \dot{q}_{tot} - \dot{q}_{HX1} - \dot{q}_{HX2} + \dot{m}_2 h_2 - \dot{m}_3 h_3 \tag{1}$$

With:

$$\frac{du}{dt} = \frac{u(P_{t+dt}, \rho_{t+dt}) - u(P_t, \rho_t)}{dt} \tag{2}$$

$$V \frac{d\rho}{dt} = \dot{m}_2 - \dot{m}_3 \tag{3}$$

$$\dot{q}_{tot} = \dot{q}_{loss} + \dot{q}_{CP} + \dot{q}_{pulse} \tag{4}$$

The internal energy variation depends on the deposited thermal loads ($\dot{q}_{tot}$), the enthalpy fluxes in and out of the loop (zero in the case of isochoric loop), the transferred loads to the liquid helium bath ($\dot{q}_{HX1}$ and $\dot{q}_{HX2}$), estimated using the physical measurements on the cooling loop: pressure, temperature and mass flow. The total energy deposited into the loop is composed of the thermal loads from the static losses along the circuit ($\dot{q}_{loss}$), from the circulating pump ($\dot{q}_{CP}$), and finally from the superconducting magnets ($\dot{q}_{pulse}$).

In order to minimize the uncertainties of the sensors and to remove the static losses from the equation, the variation of energy balance is calculated between t and t0 (the steady state behavior before the beginning of the pulse load), with, with the following convention $\Delta X = X(t) - X(t_0)$:

$$\dot{q}_{pulse}(t) = \rho(t) V \frac{du(t)}{dt} + \frac{d\rho(t)}{dt} V u(t) - \Delta(\dot{m}_2 h_2) + \Delta(\dot{m}_3 h_3) + \Delta\dot{q}_{HX1} + \Delta\dot{q}_{HX2} - \Delta\dot{q}_{CP} \tag{5}$$

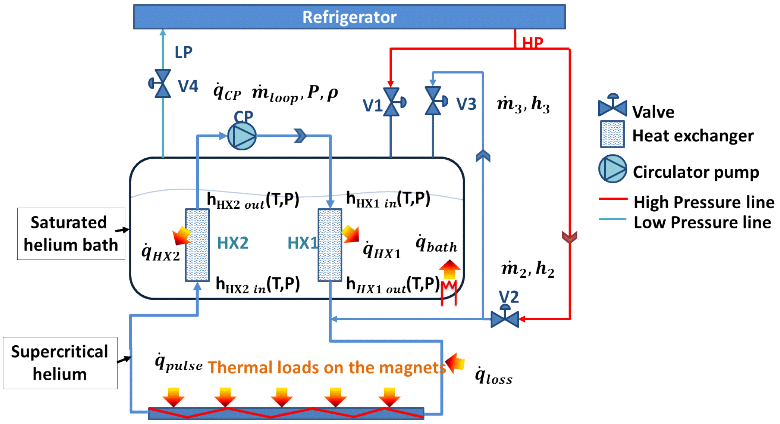

Fig 1.: Schematic of a cooling loop of a superconducting magnet with forced flow supercritical helium

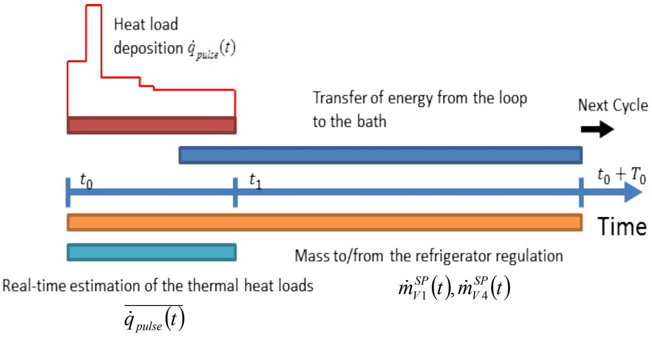

Fig 2.: Heat load estimator and pulsed load smoothing regulation

In isochoric loop, the equation (5) is simplified as follows:

$$\dot{q}_{pulse}(t) = \rho(t)V\frac{du(t)}{dt} + \Delta\dot{q}_{HX1} + \Delta\dot{q}_{HX2} - \Delta\dot{q}_{CP} \qquad (6)$$

The integral of previous equation over a time t gives the energy deposited on the loop from t0 to t. If this time t is equal to the cycle period T0, we recover the pulse energy:

$$\overline{\dot{q}_{pulse}(t)} = \int_0^t \dot{q}_{pulse}(t)dt \qquad (7)$$

2.3. Application to heat load smoothing

With the estimation of the average heat loads deposited into the loop $\overline{\dot{q}_{pulse}(t)}$, controls of the mass flows in and out of the liquid helium bath can be adjusted in real time, starting from the beginning of the cycle t0 (Fig. 2). The evaporation mass flow shall be compensated by the liquid fraction of the inlet mass flow *(1-x)*. The evaporated helium depends on the heat loads from the loop and from the bath.

The initial mass flow set points are calculated at the equilibrium conditions at t0, with the stationary loads.

$$\dot{m}^{SP}_{V1,ini} = \dot{m}^{SP}_{V4,ini} = \frac{\dot{m}_{evap}}{(1-x)} = \frac{\overline{\dot{q}_{tot}} + \overline{\dot{q}_{bath}}}{L_{sat}(1-x)} \qquad (8)$$

The mass flow set points are adjusted along the cycle with the variation of $\overline{\dot{q}_{pulse}(t)}$, as the other heat loads are known and stationary :

$$\dot{m}_{V1}^{SP}(t) = \dot{m}_{V4}^{SP}(t) = \dot{m}_{V1,ini}^{SP} + \frac{\overline{\dot{q}_{pulse}(t)}}{L_{sat}(1-x)} \tag{9}$$

3. Experimental validations

The methodology has been tested and validated on HELIOS test facility in the isochoric configuration, with a pulse scenario of 1800 s. The pulsed load smoothing strategy is the thermal buffer one: the control valve V4 is limiting the mass flow to the refrigerator. During the pulse, the energy is stored into the liquid helium bath and is released progressively to the refrigerator the remaining part of the cycle. The set point for the mass flow $\dot{m}_{V4}^{SP}(t)$ is calculated with the heat load estimator.

Four cycles have been tested in series, with a decrease of the thermal load profiles by a factor power from 1 to 0.7 (Fig. 3). The difference of between 9% and 16% between the real and the estimated heat loads show the efficiency of the method (Table 1). A small delay is observed for the estimated heat load profile which is partly due to the position of the thermometers: they are not exactly located at the inlet and outlet of the heat exchangers and hence induce some time shift in the estimation of the transferred thermal loads to the bath

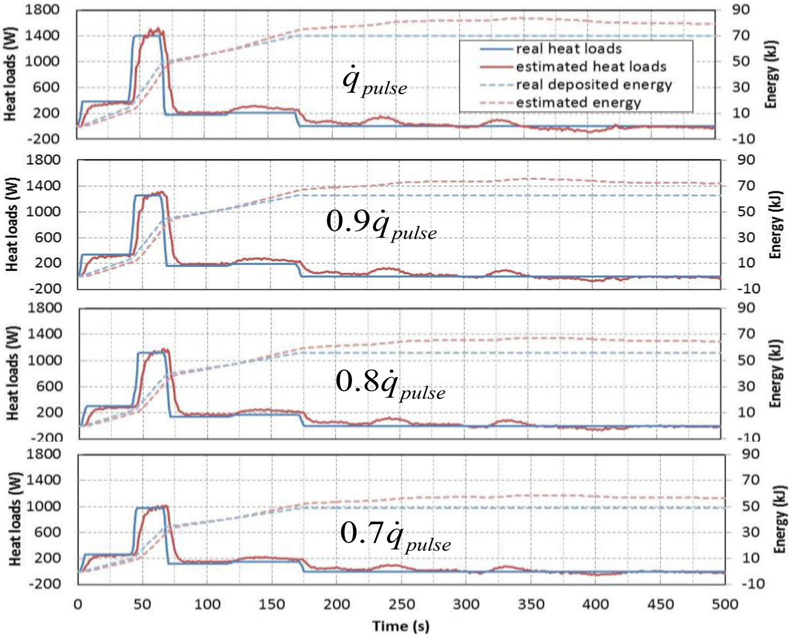

Fig. 3. Comparison of the real and estimated heat loads (a) $\dot{q}_{pulse}$; (b) $0.9\dot{q}_{pulse}$; (c) $0.8\dot{q}_{pulse}$; (d) $0.7\dot{q}_{pulse}$

Table 1 gives the error on the deposited energy, which increases when the factor applied on $\dot{q}_{pulse}$decreases. The overestimation is at least 9%, which is conservative for the setting of the maximum mass flow to refrigerator.

Table 1. Error estimation of the energy for the 4 cases

Factor on power	$1\ \dot{q}_{pulse}$	$0.9\ \dot{q}_{pulse}$	$0.8\ \dot{q}_{pulse}$	$0.7\ \dot{q}_{pulse}$
Error on estimated energy	+9 %	+13 %	+15 %	+16 %

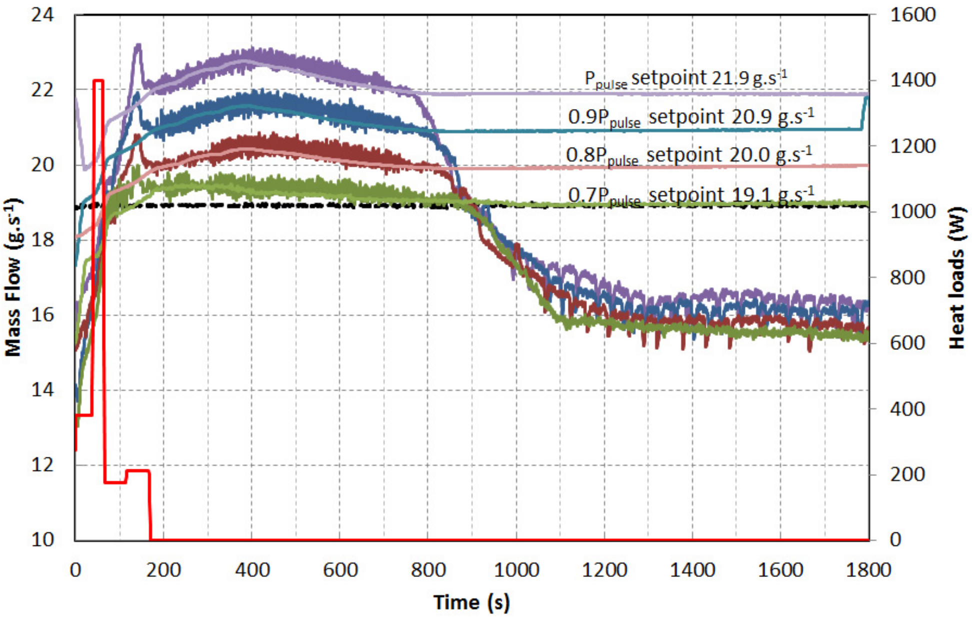

Fig. 4. Mass flow to the refrigerator and pulsed heat load scenario

Fig. 4 shows the controls on the mass flow to the refrigerator in the four cases. We observe an increase of the set point from 19.1 g/s to 21.9 g/s when the factor on power is increased. The small bumpy shape of the set point is related to the decrease of the latent heat of vaporization between t = 200 to 900 s, when the liquid helium bath is pressurized. This effect is less important for the factor power 0.7, as the pressurization of the bath is lower.

4. Conclusions

The experimental campaign on HELIOS has validated the heat loads estimator method, directly implemented into the PLC. The heat load estimation is conservative, with a maximum overestimation of +16%. It relies on physical measurements on the loop (pressure, temperature at the inlet and outlet of the heat exchangers, mass flow). Taking advantage of the transport time in the cryogenic distribution, the pulse loads can be anticipated and the refrigeration power can be controlled accordingly. This method can find interesting applications when the operating mode of the tokamak changes (for example from stand-by to plasma mode): the refrigeration is flexible and adapts its load to the need. For non-expected events such as plasma disruption or fast discharge of the superconducting magnets, the heat load estimator can calculate the high variable loads before it affects the refrigerator and hence safely secure the cryogenic system.

References

[1] Hoa et al., Investigations of pulsed heat loads on a forced flow supercritical helium loop – Part A: Experimental
[2] Zanino R., Bonifetto R., Hoa C., and Savoldi Richard L., Verification of the Predictive Capabilities of the 4C Code Cryogenic Circuit Model, AIP Conference Proceedings 1573, 1586 (2014).
[3] EA Internacional, *EcosimPro http://www.ecosimpro.com/description.php*. 2013.
[4] Lagier B., Hoa C., Bonnay P., Rousset B., Validation of an EcosimPro model for the assessment of two heat load smoothing strategies in the HELIOS experiment, Cryogenics 62 (2014) 60–70.
[5] Lagier B., Experimental study for a supercritical helium loop subject to pulsed heat loads, thesis, Université de Grenoble, 11 March 2014.
[6] Aigouy G. et al., Method and equipment for pulsed charge refrigeration, Patent US2013/0000332 Jan. 3,2013.
[7] Lagier B., Hoa C, Bonnay P, Procédé et dispositif de régulation d'un système de refroidissement cryogénique, Brevet FR n° BD14686SG
[8] Arp V., Mc Carty B., and Fox J., *HEPAK*. Louisville, Colorado: Cryodata Inc, 1999.