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

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Background

Superconducting magnets 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 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.

Equations

Internal energy balance applied on the loop

$$\rho V \frac{du}{dt} + \frac{d\rho}{dt} Vu = \dot{q}_{pulse} + \dot{q}_{CP} + \dot{q}_{loss} - \dot{q}_{HX1} - \dot{q}_{HX2} + \dot{m}_2 h_2 - \dot{m}_3 h_3$$

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

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

Heat load estimator in isochoric configuration

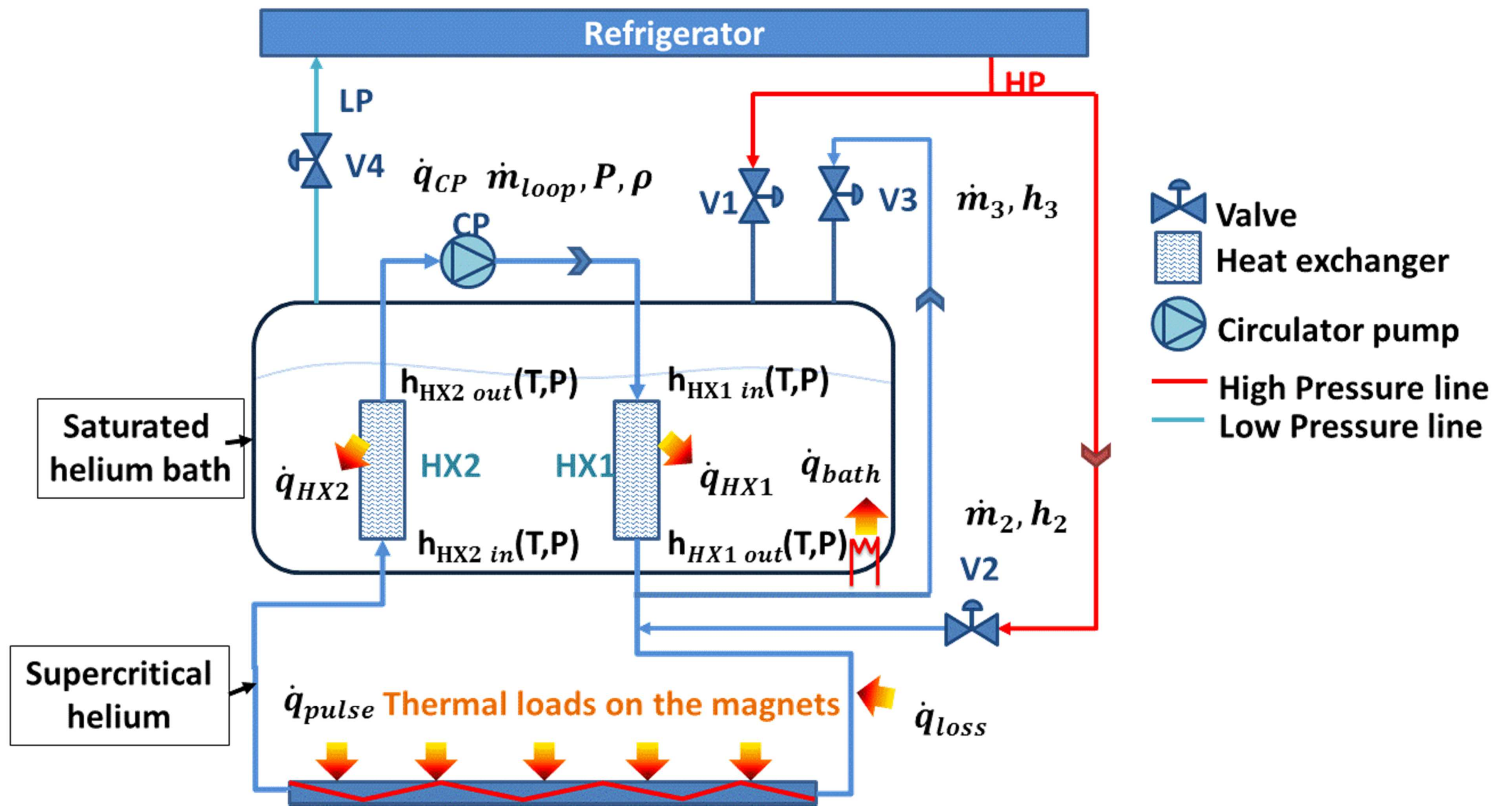
$$\dot{q}_{pulse}(t) = \rho(t) V \frac{du(t)}{dt} + \Delta\dot{q}_{HX1} + \Delta\dot{q}_{HX2} - \Delta\dot{q}_{CP}$$

With the notation $\Delta X = X(t) - X(t_0)$

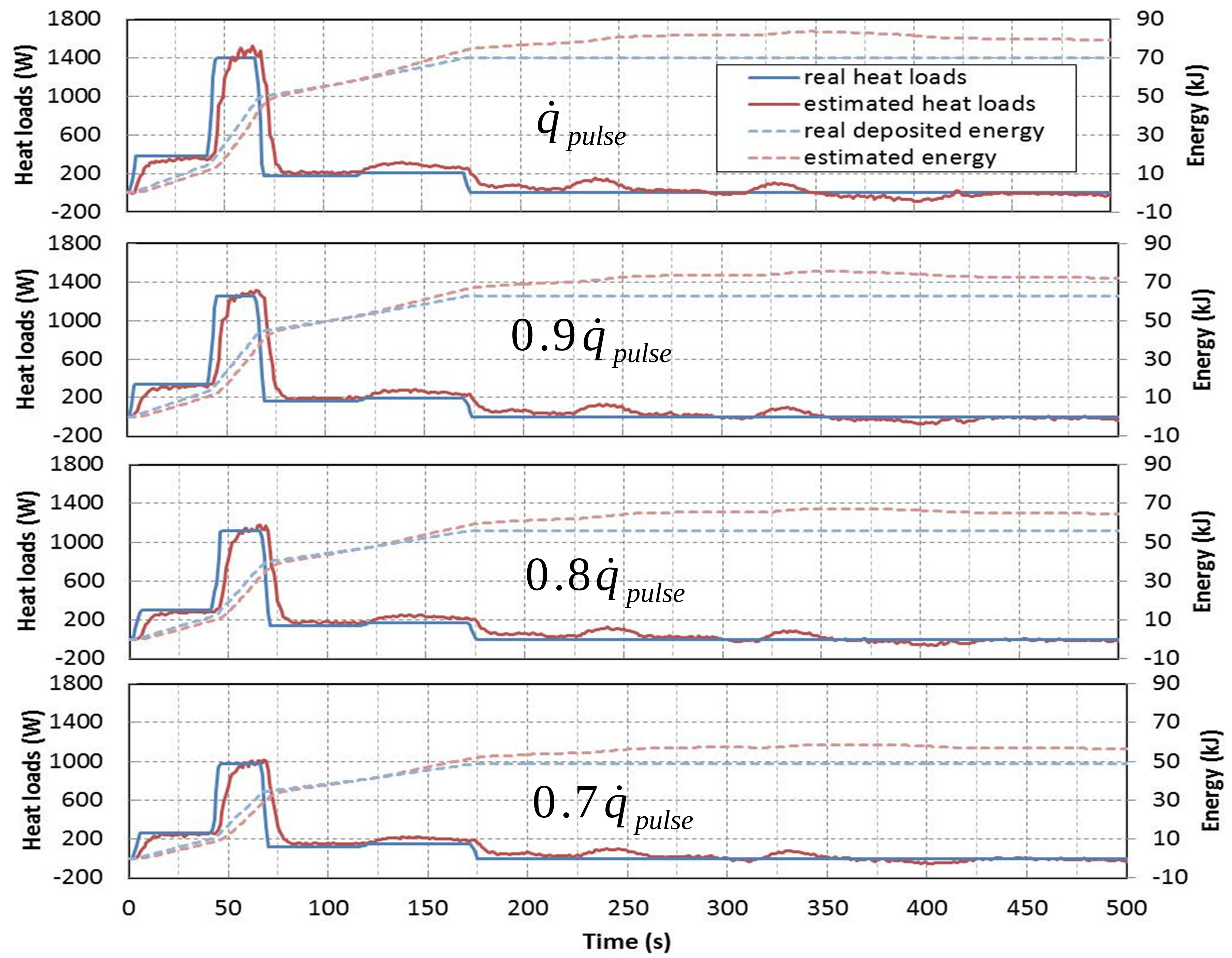
$$\overline{\dot{q}_{pulse}(t)} = \int_0^t \dot{q}_{pulse}(t) dt$$

Application to pulsed load smoothing

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

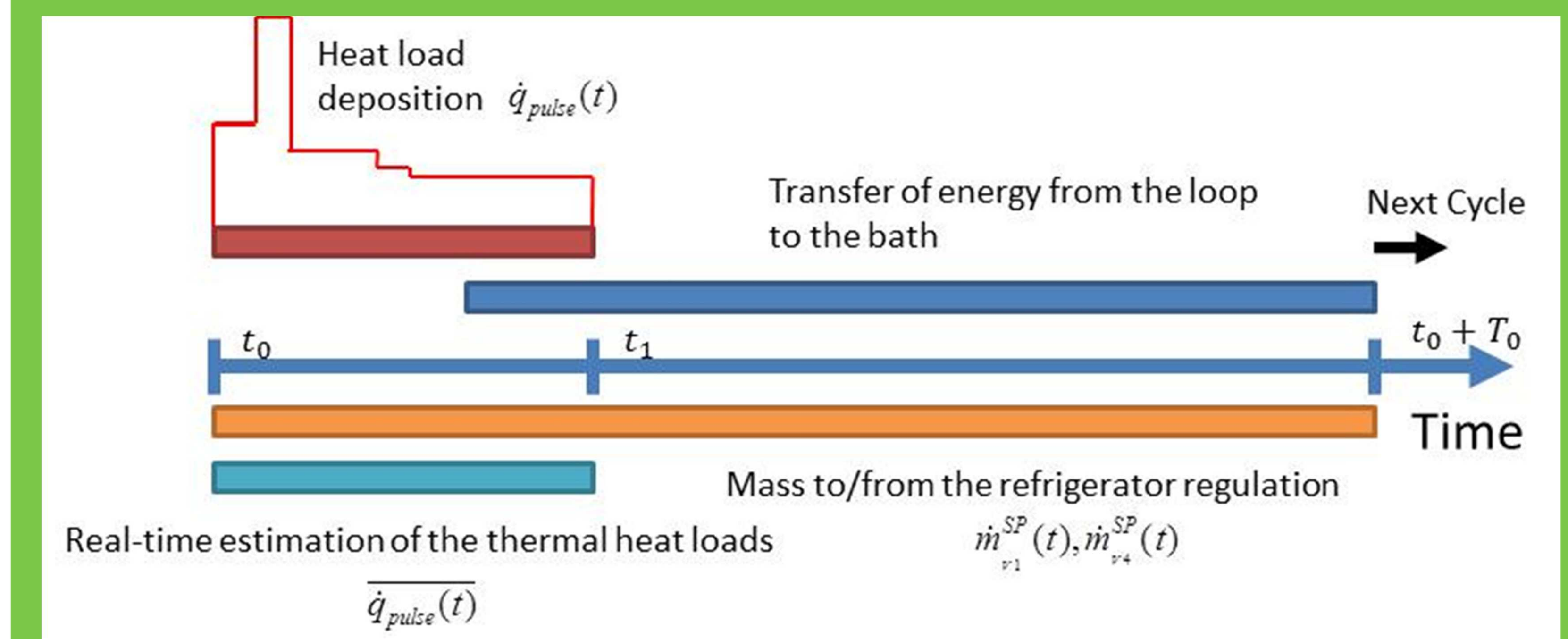


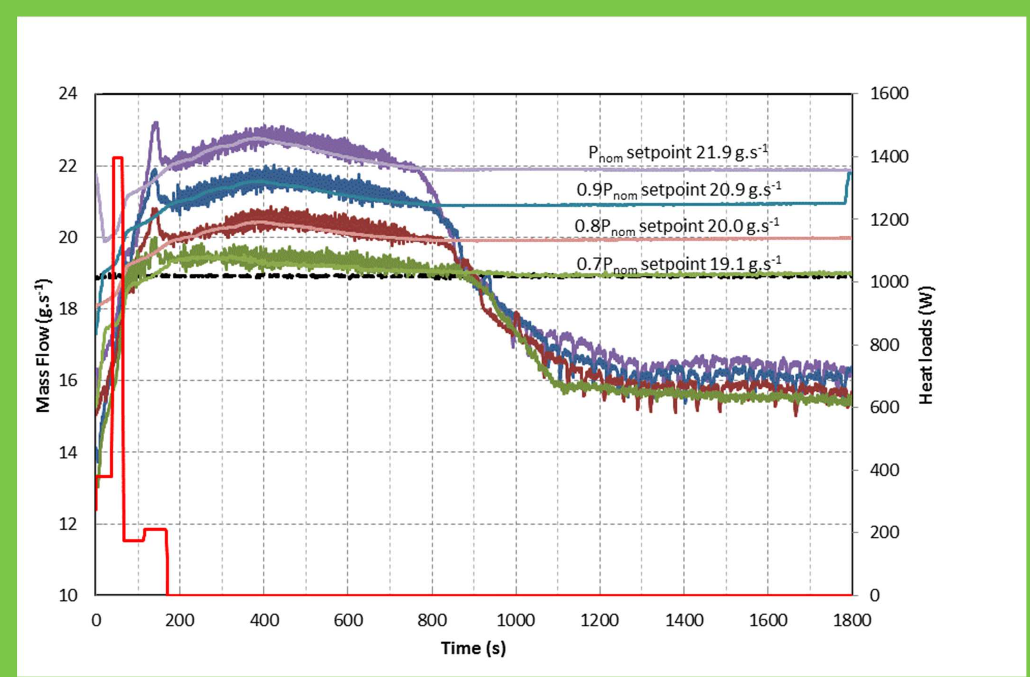
Results



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 %

Pulsed load smoothing





- Application on 4 consecutive heat load profiles, with decreasing power (factor power 1 to 0.7).
- 4 decreasing set points for the maximum mass flow to the refrigerator

Conclusion

- The experimental validation on HELIOS of the heat loads estimator method, directly implemented into the PLC.
- The heat load estimation is conservative, with an overestimation of +16%. It relies on physical measurements on the loop (pressure, temperatures 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 offers interesting applications for transient modes of the tokamak (for example from stand-by to plasma mode): the refrigeration is flexible and adapt its load to the need. For non-expected events such as plasma disruption or fast discharge of the superconducting magnets, the heat loads estimator can calculate the high variable loads before it affects the refrigerator and hence safely secure the cryogenic system.

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