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Incorporating Artificial Neural Networks in the dynamic thermal–hydraulic model of a controlled cryogenic circuit

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ABSTRACT

A model based on Artificial Neural Networks (ANNs) is developed for the heated line portion of a cryogenic circuit, where supercritical helium (SHe) flows and that also includes a cold circulator, valves, pipes/cryolines and heat exchangers between the main loop and a saturated liquid helium (LHe) bath. The heated line mimics the heat load coming from the superconducting magnets to their cryogenic cooling circuits during the operation of a tokamak fusion reactor. An ANN is trained, using the output from simulations of the circuit performed with the 4C thermal–hydraulic (TH) code, to reproduce the dynamic behavior of the heated line, including for the first time also scenarios where different types of controls act on the circuit. The ANN is then implemented in the 4C circuit model as a new component, which substitutes the original 4C heated line model. For different operational scenarios and control strategies, a good agreement is shown between the simplified ANN model results and the original 4C results, as well as with experimental data from the HELIOS facility confirming the suitability of this new approach which, extended to an entire magnet systems, can lead to real-time control of the cooling loops and fast assessment of control strategies for heat load smoothing to the cryoplant.

1. Introduction

In tokamak-type fusion reactors, like ITER, the confinement of the plasma is obtained through superconducting (SC) magnets which are cooled by supercritical He (SHe) [1]. Sophisticated (and therefore complex) thermal-fluid-dynamic codes, like, for example, the 4C code [2], are available for the detailed and accurate thermal–hydraulic (TH) modeling of SC magnets and their cryogenic circuits. The large computational effort needed by these codes, capable to return an accurate and detailed information about the evolution of the TH transients everywhere in the magnets, makes them inappropriate for a future real-time control of the reactor operation where just few selected information are relevant, so that faster but simplified models must be addressed.

Soft computing techniques, like Artificial Neural Networks (ANNs) [3], have shown in the past a great potential of reducing by orders of magnitude the computational effort with respect to physics-based models, with a small loss in accuracy, for different kinds of applications. In the context of cryogenic circuits for SC magnets, ANNs have been recently introduced and successfully applied [4] to the HELIOS loop [5], as well as to the more complex problem of the ITER Central Solenoid (CS) [6] and Toroidal Field (TF) coils [7] cooling circuit, confirming their capability to predict the evolution of the heat load to the cryoplant during plasma operation, *in the case when no controls act on the circuit*.

Here we develop an innovative ANN-based approach to model the dynamic TH behavior of the HELIOS loop, when controls act on it. First we derive the model, then a benchmark is carried out by comparing the results of the ANN-based model with those of the 4C code, when different types of control scenarios are applied. A comparison with experimental data from HELIOS is also presented. The expected output of this work is the proof of the feasibility of the use of ANN in a controlled circuit rather than the demonstration of the gain in computational time with respect to the original 4C code, since in fact the 4C model of the HELIOS heated line, see below, is already very simple and fast in execution. The approach presented here is expected, on the contrary, to lead to huge gains in computational time when extended to the cooling loop of an entire SC magnet [7].

2. ANN-based model

The starting point for the development of the simplified model is the already available 4C model of the HELIOS SHe loop,

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Nomenclature

ANN	Artificial Neural Network
BC	boundary condition
CS	Central Solenoid
C#	cryoline #
Exp	experimental
FE#	Venturi flowmeter #
h	Helium specific enthalpy (J/kg)
He	Helium
HELIOS	HElium Loop for hIgh LOads Smoothing
H#	Heated sector #
HX	Heat eXchanger
ITER	International Thermonuclear Experimental Reactor
LHe	Liquid Helium
$\dot{m}$	Helium mass flow rate (g/s)
P#	pressure sensor #
p	Helium pressure (bar)
Q	power (W)
SC	superconducting
SHe	supercritical Helium
T	Helium temperature (K)
TH	Thermal–hydraulic
T#	temperature sensor #
t	time (s)
V#	valve #
4C	Cryogenic Circuit Conductor and Coil code

Greek

ε	error

Subscripts

bath	He bath
i	index
in	inlet
H#	Heated sector #
out	outlet
0	reference
SS	steady-state

whose details can be found in [8–10], see Fig. 1. The HELIOS loop is constituted by a cold circulator, a heated line with three heated sectors (H1, H2, H3), mimicking the heat load (Q_{H1}, Q_{H2}, Q_{H3}) coming from the SC magnets, different cryolines (C#), control valves (V#) and two heat exchangers (HX1 and HX2). The HX2 releases the heat load coming from the heated line to the saturated liquid He (LHe) bath, acting as a thermal buffer to smooth the heat load to the refrigerator, which is not modeled in 4C. The aim of the HX1, instead, is to keep as much as possible T_{in}, i.e. the temperature at the inlet of the heated line, close to the LHe bath temperature T_{bath}, and to release to the thermal buffer the load coming from the circulator work. The

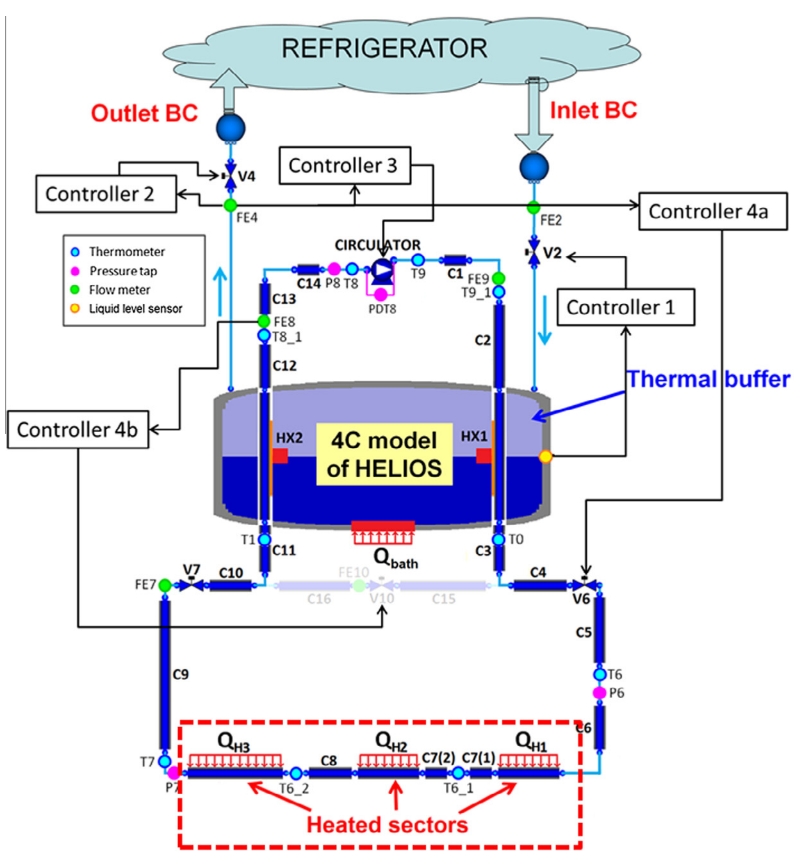

Fig. 1. 4C model of the HELIOS loop. The portion of the circuit modeled with ANNs in the present paper is identified by the red dashed boundary. The by-pass branch (in transparency), always closed during normal operation, is used for specific scenarios and modeled only when needed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)