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Simplified thermal model of the ITER magnet system

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ABSTRACT

A simplified thermal model of the ITER magnet system has been developed to capture the essence of the magnet heat load dynamics without the need for extensive computations. Idealization of the magnets has been made using mainly two standard types of elements, solids and tubes. No Navier–Stokes equations have been solved for the hydraulics, but instead a simple transport model with approximation for pressure evolution has been used. The model was implemented in C language and used to investigate the important features needed to implement a computationally efficient and fast magnet thermal model capturing overall behavior in terms of superconductor cooling channel description (thermal coupling with jackets, presence of the conductor, importance of the central channel, etc.). Furthermore, the model was benchmarked against validated simulation tools such as SuperMagnet and Vincenta using the ITER Central Solenoid normal operation scenario for comparison. Dynamics were shown to be reproduced in good agreement with results attainable with these more detailed codes, considering the high level of uncertainty on the input parameters, namely the heat transfer coefficients and the values of heat loads.

1. Introduction

1.1. Context of this work

The fast changing magnetic fields required for the operation of the fusion reactor ITER (currently in design and construction) are achieved thanks to a magnet system based on superconducting coils. During the normal operation of the machine, the magnet structure and the conductor itself are subject to time-varying non-uniform thermal heat loads of diverse origins (nuclear radiation, eddy currents, Ohmic losses in joints, AC losses in superconductors, etc.). The ITER magnets are based on cable-in-conduit conductors (CICC); superconducting strands are disposed in bundles inside a pipe through which supercritical helium flows. The heat loads generated in the magnets are transported by the fluid to the cryoplant, composed of a set of heat exchangers that on the secondary side are in contact with a boiling helium bath. From there the heat is transferred to a refrigeration cycle that ultimately removes it from the circuit [9].

Thermal modeling of the ITER magnet system needs to account for two main aspects. Firstly, assessing conductor temperature both along the entire length of the flow path, and over time during the transient, to verify that a sufficient thermal margin exists throughout the plasma scenario. Secondly, a good temporal (dynamic) estimate of the energy being carried away from the magnets to the cryoplant by the outlet helium flow is need. In turn, this information can be used to assess the heat load the cryoplant needs to manage so that magnet inlet temperature is kept constant despite a heavily pulsating heat load. Models should be able to reproduce the magnets dynamics taking as an input the helium flow conditions provided by the cryoplant and a heat load scenario, and returning as an output the helium outlet conditions, that constitute the inlet of the cryoplant and its heat load condition (see Fig. 1).

The tools currently available to analyze the conductor margins are highly detailed models that describe thoroughly the system with most of its elements and their thermal interactions. They are capable of producing accurate distributions of temperature along the flow paths over time as required to assess the conductor operating margin. However, they tend to be extremely detailed (and hence slow) for the purpose of assessing the overall heat load and its effect on the magnet/cryoplant interface.

The intention behind this work is to develop reasonably accurate, yet very simplified, thermo-hydraulic models of the ITER magnets that could capture the overall transient heat load response as seen by the cryoplant, and to do so with as few elements as possible thus optimizing the computational efficiency. It is

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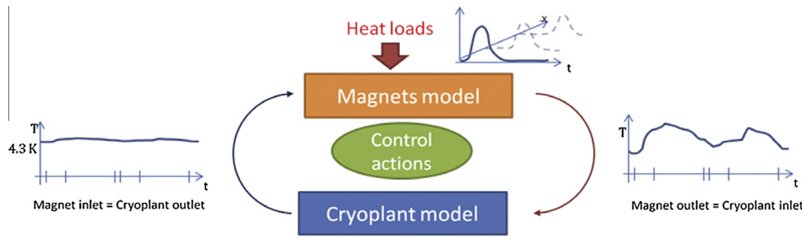

Fig. 1. Schematic of the magnet/cryoplant interface.

essential that these models represent as accurately as possible the time behavior transfer function from magnet heat load to cryoplant heat load, without much concern for calculating temperature distributions inside the magnet system itself. It is highly desirable that the execution be fast (preferably faster than real-time) so as to use the models in design iteration loops, control strategy exploration and evaluation and, eventually, as a predictive control tool in real time operation of the ITER machine.

1.2. Background on the ITER magnet system

In this section, the main design features of ITER magnets relevant to the development of the simplified thermal model are highlighted. A detailed description of the ITER magnets and their manufacturing process can be found in works by Mitchell et al. [6], Mitchell et al. [7] and Devred et al. [2].

In ITER's CICCs the superconducting strands are placed in bundles in the annular space, separated from the central channel by a stainless steel spiral. The central channel provides a low-resistance path to the helium flow, whereas fluid exchange is possible between the channel and the cable space. The conductor is contained in the stainless steel jacket, which can be either square or circular, depending on the magnets. As an example, a picture of the cross section of ITER Central Solenoid (CS) conductor is shown in Fig. 2.

Conductors are wound into flat pancakes, which are then stacked and connected to make coil modules. Coolant is injected by feeders every two pancakes in such a way that alternate pancakes have contrary helium flow directions. The feeders are placed at the innermost turn of the pancake. Helium is collected at the outermost turn.

To summarize, a magnet cross section is composed of parallel pipes separated by solid structures. Pipes on the same row have the same flow direction – either into or out of the cross section – but those in alternate rows are in counterflow.

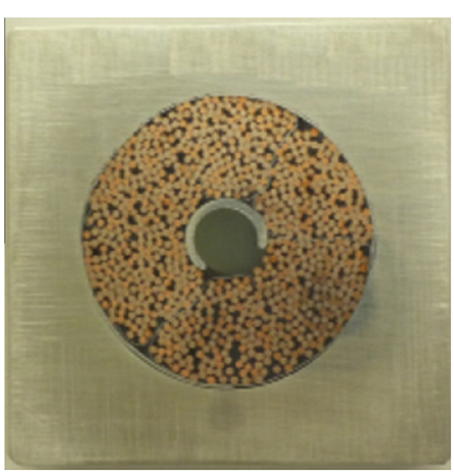

Fig. 2. Cross section of the ITER CS conductor.

Tubes in the magnet conductor are just a part of the cryogenic hydraulic network, which also includes the heat exchangers in the cryoplant, pumps, valves, distribution lines and feeders, connection volumes and other elements. These are, in turn, modeled using lumped parameter/flow models. One of the main objectives of this work is to create an equivalent model of the magnet (including its heat loads) for magnet/cryoplant interface integration studies.

2. Simplified thermal model

The model proposed in this work relies on a generic and simplified representation of a superconducting magnet system, its flow paths, heat capacities, and heat loads during operation. In a first stage an idealized simplified magnet cooling network needs to be created. The idealization may consist of combining several identical parallel branches into a single equivalent pipe, the unification of several structure parts, etc. The next step is to fit that idealization into the representation constructed with the elements presented in Section 2.1.

2.1. Elements of the model

The simplified model consists of an ideal hydraulic network representing the magnets and the cryogenic pipelines connecting them to the cryoplant. This network is constructed using three types of elements:

1. Tubes: elements that transport fluid, transferring inlet properties to the outlet with a transit time depending on mass flow rate, density and volume, incorporating heat input to the fluid and pressure changes.
2. Solids: structural elements that can accumulate thermal energy (heat capacity) and exchange it with tubes and other solids.
3. Connection nodes: elements of the hydraulic network with many inlets and/or outlets that mix incoming flow and provide a homogeneous output.

For purposes of modeling, each coil is subdivided into a number of elements. Each of these elements, called hereafter 'magnet element', has a particular cross section composed of solid and tube cross sections. Some of these tubes have parallel flow, so they can be considered equivalent and could be condensed into a single lumped element. Several solid parts may have a very similar temperature and heat load condition, so they could be lumped into a single solid element as well. Thus, a simplified cross section of the magnets can be represented using fewer tubes and solids than in the real magnet. Different magnet elements are then connected in series by interconnecting the outlets and inlets of their tubes. This way a simplified hydraulic network representing a magnet can be constructed.

Connection nodes and tubes are also used to construct the external hydraulic networks. Connection elements may or may