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Development of the Cryogenic Circuit Conductor and Coil (4C) Code for thermal-hydraulic modelling of ITER superconducting coils.

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We report on the status of development and first preliminary applications of a new computational tool – the 4C code – for the thermal-hydraulic simulation of the entire ITER magnet system.

INTRODUCTION

A new computational tool – the 4C code – is being developed, which allows in principle the thermal-hydraulic simulation of the entire magnet system of the International Thermonuclear Experimental Reactor (ITER), with particular reference to the conductors in the coil winding, the structures and the refrigeration circuit. Such a tool can be useful for several tasks in the assessment of the operating scenarios of the reactor and in particular at predicting the coil performance in terms of temperature margin, as well as at simulating the overall heat loads to the cryoplant and the control of the helium flows. Here we concentrate on the case of the ITER Toroidal Field (TF) coils.

MODEL OF THE CRYOGENIC CIRCUIT

The supercritical helium (SHe) cryogenic circuit foreseen in ITER for the refrigeration of the coils is constituted by four parallel loops as shown in Fig. 1: TF, TF structures, Poloidal Field coils and Central Solenoid [1]. Each loop presents active components (two pumps in parallel for redundancy), a heat exchanger to the liquid helium (LHe) bath with a bypass valve to smooth the heat load to the bath [1], and cryolines, which connect the helium bath to the coils/structures.

In the case of the TF coils, two separate circuits must be modelled: one for the winding and one for the structures (case). Each of these circuits can be described as the modular connection of several discrete components (valves, pumps, cryolines, etc.). Instead of writing ad-hoc Fortran or C code, another approach has been followed, based on the object-oriented, equation-based modelling language Modelica [3-5], and of ad-hoc libraries of Modelica components [6-7]. The Modelica code is then translated into an executable

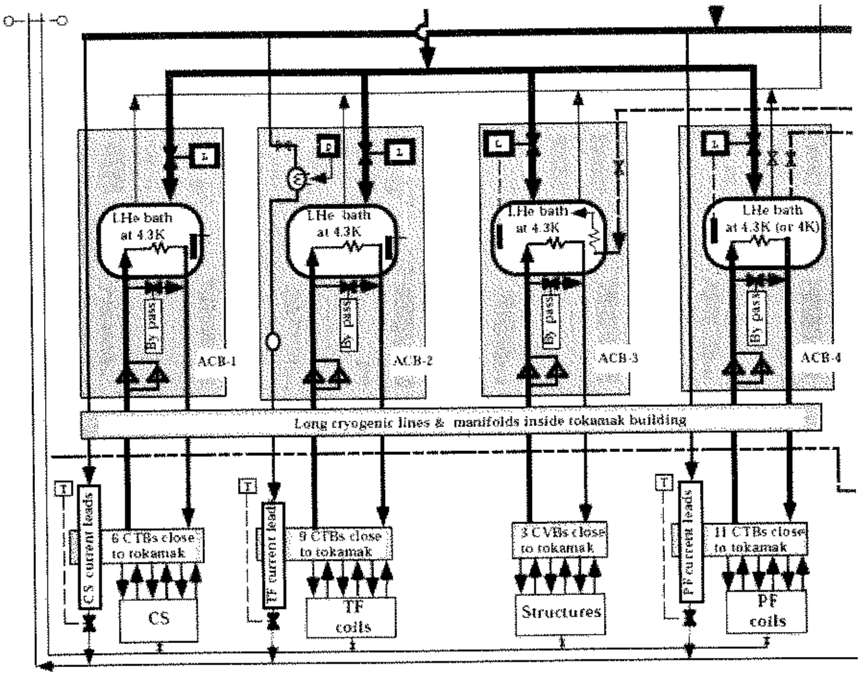

Figure 1 Schematic view of the ITER cryogenic circuit for coil refrigeration (reproduced from [1])

simulation code using a commercial software [8].

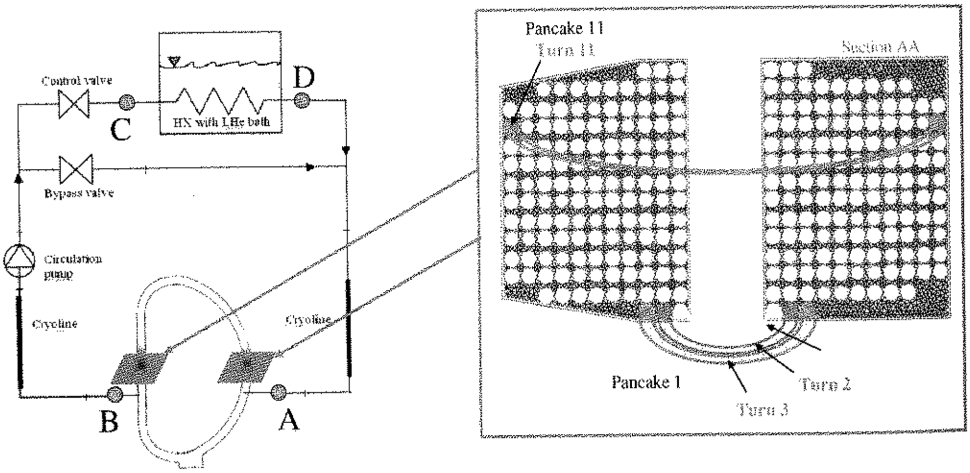

Figure 2 Cryogenic circuit, coil and conductor winding model for an ITER TF coil. The SHe inlet is located in turn 1, at a poloidal location between the two sections. The flow is actually in opposed directions in neighboring pancakes, but assumed here to be in the same direction, for the sake of simplicity.

We now consider each component separately, see Fig. 2: the circulation pump is modelled as centrifugal; the heat exchanger is modelled by a 1D finite volume model of the helium flow, with convective heat transfer through the lateral surface with the helium bath; the LHe bath is represented for the sake of simplicity as a reservoir with prescribed saturation temperature; the two cryolines are represented with the same 1D model used for the heat exchanger, but adiabatic. Finally, the TF coil "component" embeds the interface with the external coil model, which is described in the next section.

The fluid circulating in the circuit is SHe; the fluid properties are computed by the same Fortran routines used for the TF coil model, wrapped up with a suitable Modelica interface [9].

MODEL OF THE TF COIL

The coil is made of superconducting cable-in-conduit conductors (CICC), shown in Fig. 3a, wound in radial plates [10] and surrounded by a case (not treated here), which is independently cooled. Radial plates and case constitute the so-called "structures".

Thermal-hydraulic model of the winding.

The M&M code [11] is used to model the winding, describing it as a set of CICC; in each CICC the 1D compressible flow of SHe (separately in the annular cable region and in the central channel, see Fig. 3a), coupled to 1D heat conduction in the strands and in the jacket, is solved. M&M was already validated against experimental data from several transients of the ITER Model Coils [12-14].

Heat conduction model for the structures.

The 3D transient heat conduction problem in the coil structures is solved approximating it with 2D heat conduction problems in a suitably selected number of TF winding pack and case cross sections, coupled by SHe advection along the conductors, as in [2], which dominates over conduction between different cross sections in the third (poloidal) direction. Each 2D conduction problem is solved by finite elements, imposing homogeneous Neumann (adiabatic) conditions at the outer boundary + Robin (Newton) conditions at the *conductor boundaries*. The triangular mesh (see Fig. 3b) covers the full cross section and allows flexibility of modeling details of the winding cross section geometry (insulation layers, circular conductors, wedged shape, ...). While the case and its cooling circuit are not yet included in the model, this extension is straightforward.

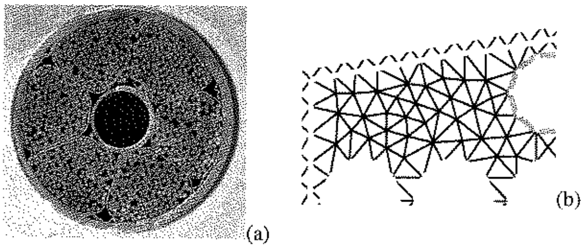

Figure 3 – a) Cross section of an ITER TF-relevant CICC, b) Detail of the triangular mesh used for the solution of the heat conduction problem in the structures (including the insulation layer)

COUPLING OF CIRCUIT, CONDUCTOR WINDING AND STRUCTURES IN THE 4C CODE

The coupling of the conductor winding and structure models is performed at each time step inside M&M. On the other hand, the coupling of the coil to the SHe circuit is performed by means of a dedicated environment: the circuit and coil models march independently in time up to the moment when the exchange of variables (inlet and outlet p and T from circuit to coil, inlet and outlet T and (dm/dt) from coil to circuit) is triggered at times defined by the user.

APPLICATIONS

Two simple types of transient, mimicking a "cooldown" and a "plasma disruption", respectively, have been simulated with the 4C code in this first phase of testing, using two different locations for the driver. A whole TF winding (14 pancakes of different lengths) is simulated with M&M, while the coil radial plates have been approximated with the two cross sections on the equatorial plane of the tokamak, see Fig. 2. In both transients the bypass valve is kept closed, the control valve is kept open.

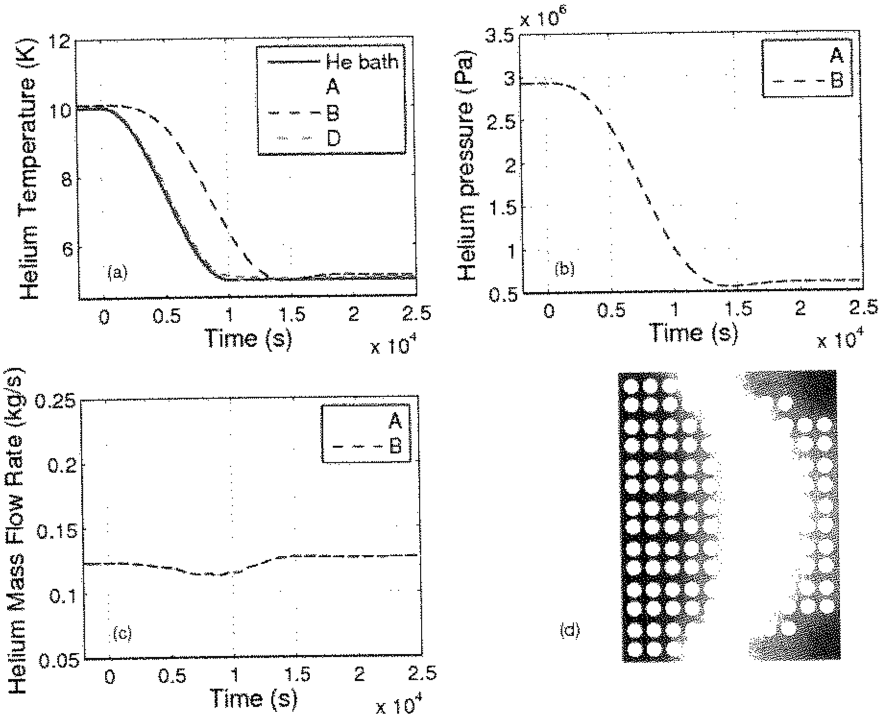

Figure 4 "Cool down" transient: evolution of temperatures (a), pressures (b) and mass flow rates (c) at different locations in the circuit; (d) temperature distribution in the cross section of the outboard radial plate at t = 10000 s.

Simulation of "cooldown" effects on one TF coil.

A decreasing temperature in the LHe bath is imposed as driver of this case, ramping down the bath temperature from 10 K to 5 K at ~ 2 K/h, then keeping it constant until a new steady state is reached. The latter is characterized by a small but finite ΔT between bath and coil inlet (Fig. 4a), due to finite heat transfer in the heat exchanger, as well as between coil inlet and outlet (Fig. 4a), due to the Joule-Thomson effect. During this transient the pressure in the circuit drops by a factor of ~5 (Fig. 4b): this reduction, combined with the temperature variation, guarantees the density to stay constant, in view of the fact that the circuit has a constant volume and helium mass during the transient. The pressure drop across the coil and the mass flow rate in the circuit (Fig. 4c) remain almost unchanged, for the same reason. The computed 2D temperature distribution on the outboard cross section of the radial plates, resulting from SHe advection along the winding, from inner (lower-index) to outer (higher-index) turns, is shown in Fig. 4d.

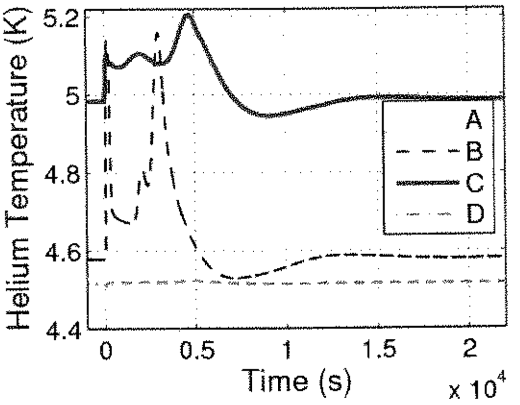

Figure 5 "Plasma disruption" transient: evolution of temperatures at different locations in the circuit

Simulation of "plasma disruption" effects on the He bath

A square wave heat pulse of 10 W/m is applied for 50 s on a 50 m length of each pancake (2nd turn + about half of the 3rd turn), mimicking a "plasma disruption". The pulse is advected by the SHe and at the same time diffuses because of the interaction with the structures. The instantaneous jump in all temperatures is due to the pressurization of the whole circuit on the sound time scale, caused by the heating, which in turn causes a temperature increase in order to maintain the total mass (and density) constant (Fig. 5). The three different peaks exiting the winding represent the outflow of hot helium from pancakes #1 and #14, #2 and #13 and the central ones, respectively, which have different lengths and thus different He transit times. The pulse is perfectly absorbed by the He bath in this case, as the outlet temperature from the bath remains constant (Fig. 5).

CONCLUSIONS AND PERSPECTIVE

The first preliminary applications of the newly developed 4C code to simple model problems have been presented. We plan to validate the code and to benchmark it against other tools (e.g., Vincenta), before applying it to transients of more direct ITER relevance.

ACKNOWLEDGMENT

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