Status and Perspectives of Thermal-Hydraulic Analysis of Superconducting Magnets for Nuclear Fusion Applications

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Abstract. An overview is presented of the work performed over the last years at Politecnico di Torino in the field of thermal-hydraulic modeling of superconducting magnets for fusion, with particular reference to present International Thermonuclear Experimental Reactor (ITER)-related activities, and to future possibilities and needs. The two-fluid Mithrandir code and its multi-conductor version, the M&M code, are used together with the cryogenic network solver Flower. We discuss the capabilities of these validated tools to simulate the evolution of thermal-hydraulic transients characterized by widely disparate time scales, from heat slug propagation to quench, both in single dual-channel conductors like that of the QUELL experiment, and in the ITER model coils (central solenoid CSMC, toroidal field TFMC).

1. Introduction

Superconducting magnets for fusion applications, in particular for ITER, will be based on low critical temperature materials (e.g., Nb3Sn or NbTi) because of the combined needs of high current density and magnetic field. Supercritical helium in forced convection will be used as a coolant to guarantee that the conductor safely operates below the current sharing temperature T_{cs}, above which a normal zone would be initiated, possibly evolving into a quench of the coil. Thermal-hydraulics becomes therefore a central issue in design and operation.

A peculiar aspect of the ITER cable-in-conduit conductors (CICC) is that the strands occupy only an annular region (cable bundle) around a central channel (hole), i.e., they have a dual-channel topology, see FIG.1. The purpose of the hole is mainly to provide a low impedance path for the coolant and a pressure relief volume if a local heating occurs in the bundle.

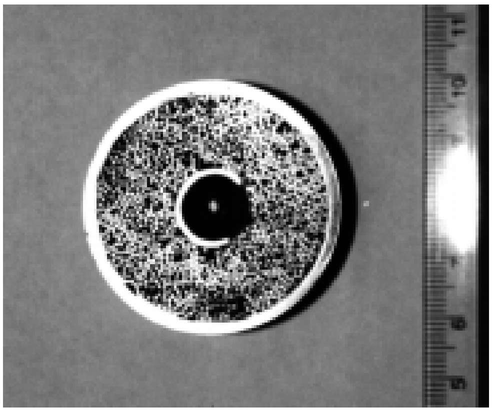

FIG. 1. Cross section of the TFMC Nb_3Sn conductor

After a first stage of tests of single two-channel CICC in the nineties (QUench Experiment on Long Length (QUELL), at Villigen PSI, Switzerland, QUench Initiation and Propagation Study (QUIPS) at Bechtel Corp., San Francisco, USA, etc.) the experimental development has now reached the stage of the ITER model coils (CSMC at JAERI Naka, Japan [1], and TFMC at Forschungszentrum Karlsruhe, Germany [2]). The corresponding evolution of the tools for thermal-hydraulic analysis will be discussed in the next Section.

2. Single-Conductor (1D) Model and Code Development

The two-channel design of the ITER CICC led some years ago to the development of the two-fluid code, Mithrandir [3], where different thermodynamic state of the helium in the two regions can be described. In particular, a separate set of 1D, time dependent Euler-like equations, augmented by sources and friction, is solved for the pressure, temperature and flow speed of helium, in each of the two regions, and coupled to separate 1D transient conduction in the strands, and in the jacket/insulation. The code was first validated [4,5] against quench data from QUELL, and showed very good accuracy compared with its parent, the 1-fluid code Gandalf [6]. It was however with the study of heat slug propagation in QUELL [7] that the essential need for, and accuracy of a 2-fluid model became apparent. Here the very low flow speed gives very low heat transfer coefficients, i.e., very low thermal coupling between cable bundle and hole, leading to significant temperature differences of the helium in the two regions, and to the failure of the 1-fluid model (indeed, as a result of this, also the Gandalf code was very recently updated to 2-fluid).

The need of developing a self-consistent predictive tool, independent of measured boundary conditions at conductor ends, led to the development of the Flower code [8] at Cryosoft, for the thermal-hydraulic description of fairly general cryogenic networks/circuits. We eventually coupled Mithrandir to Flower [9], obtaining very accurate simulations of quench propagation in QUELL, where the conductor controls the evolution of the transient. A stronger sensitivity to details of circuit model was shown on the contrary in the case of heat slug transients.

On the way from single conductor to full coil simulations, the Mithrandir model was then extended to include the joints, i.e., variable geometry (e.g., helium flow area) and materials along the hydraulic path [10].

3. Multi-Conductor (Quasi-3D) Model and Code Development

While all of the above-mentioned studies were based on single conductors, the need for the treatment of a full coil, e.g., the ITER model coils, has very recently led in a natural way to the development of the Multi-conductor Mithrandir (M&M) code [11], which can describe thermal-hydraulic transient evolution in an arbitrary number of thermally and/or hydraulically coupled dual-channel conductors, in parallel or in series.

M&M, at present arguably the most complete and accurate tool for thermal-hydraulic modeling of superconducting magnets for fusion, is being applied to the analysis of the test program of the CSMC and TFMC. In particular, the T_{cs} measurement data from the CSMC have been successfully reproduced with the code (see FIG.2 and [13]), and a systematic predictive study of T_{cs} tests in the TFMC has been initiated, leading to some surprises [14].

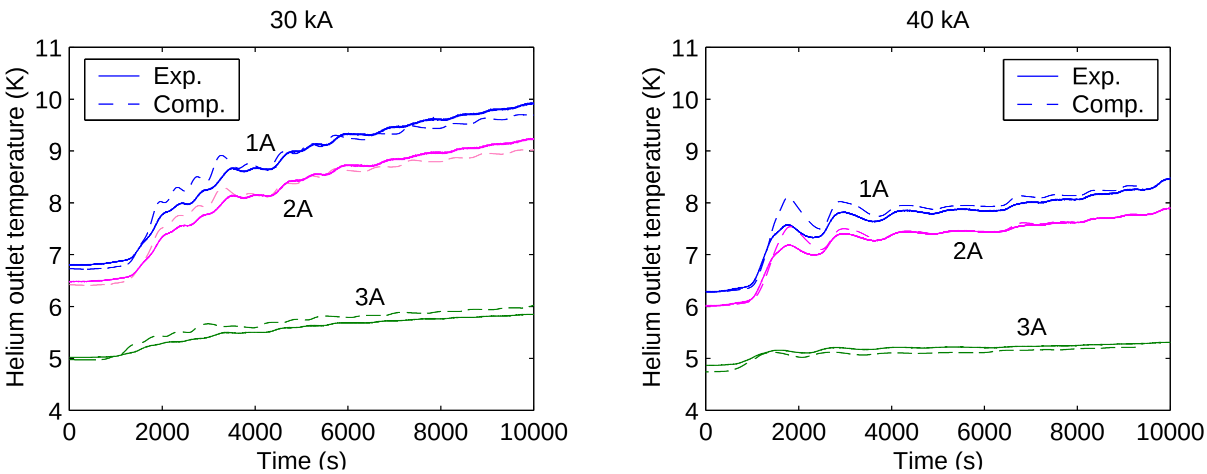

FIG.2. Comparison between experimental data (solid lines) and M&M results (dashed lines) during T_{cs} measurement in the CSMC, at different transport currents. The hour-long evolution of helium temperatures at the outlet of conductors 1A, 2A, and 3A is shown, driven by the step increase of input power from a resistive heater upstream of, and in common to layers 1-2, until the current sharing temperature is reached. The complex cryogenic circuit model is used [13].

The single-conductor models as implemented, e.g., in the Mithrandir or Gandalf codes, are 1D (along the hydraulic path) because of the large mismatch between transverse size (~ 10^{-2} m) and longitudinal size (~ 10^{2} m). Now, the novel multi-conductor model has allowed, in a sense, the major extension of CICC analysis to intrinsically multidimensional situations, e.g.:

a) Quasi-2D heat exchange between the half joints in a lap-type configuration [12] - an essential sub-item in coil modeling;
b) Quasi-3D analysis of a full coil (see FIG.3);
c) Quasi-3D analysis of heat and mass transfer among sub-channels in a CICC (see FIG.4).

In all cases, good agreement with the experiment was shown.

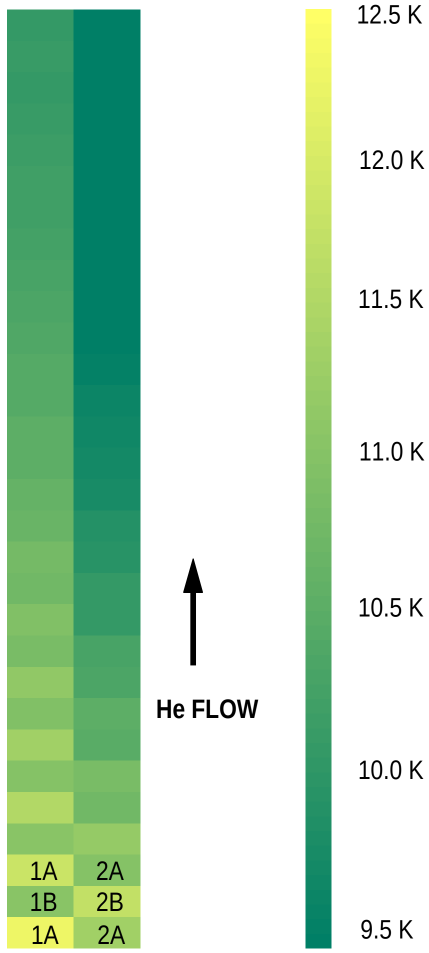

FIG. 3. Quasi-3D helium temperature distribution computed with M&M in the CSMC as T_{cs} is reached at 30 kA, see also FIG. 2. Only the innermost two layers are shown in a vertical cross section through the coil symmetry axis (to the left of the figure, not shown). Hot helium enters the coil from below, and is cooled by inter-turn (e.g., 1A with 1B), inter-layer (e.g., 1A with 2A, or 2A with 3A, not shown), and joint (e.g., 1A with 2B, or 1B with busbar, not shown) heat conduction, together with heat conduction/convection along each conductor. See also [13] for details.

4. Needs and Routes for Further Development in CICC Thermal-Hydraulics

From the point of view of pure thermal-hydraulics it may be observed that in present-day models a number of uncertainties, at the single-conductor level, are hidden in the friction factors (*ff*) and heat transfer coefficients (*htc*), used to lump in a single parameter the boundary layer coupling between helium and solids in a CICC. Several dedicated experiments have been performed over the years to experimentally assess the *ff*, separately in the cable bundle and in the central regions. These data have been used to obtain correlations (see, e.g., [15]), which although sometimes ad-hoc are relatively reliable, at least if used strictly within the range of parameters (Reynolds number *Re*, etc.) for which they were originally developed. Not the same can be said of the *htc*. For instance, the Dittus-Boelter correlation is routinely used in most codes for the *htc* between helium and strands (typically at low *Re*), while it was originally developed for circular pipes at high *Re*, and attempts to simulate the global heat exchanger features of a joint have clearly highlighted the risks of such an extrapolation. Therefore, it appears to us that a more systematic, theoretical/numerical/experimental development should be needed in this field. For instance, the treatment of the cable bundle region as a porous medium appears promising in providing a unified approach to the fundamental problem of thermal-hydraulic characterization of a two-channel CICC, and we are planning to pursue it further. Finally, when moving to the coil level, more and more complex models of the whole cryogenic circuit will be needed to adequately capture actual transients, see [14-15].

All of the modeling we have discussed until now is purely thermal-hydraulic, and the current

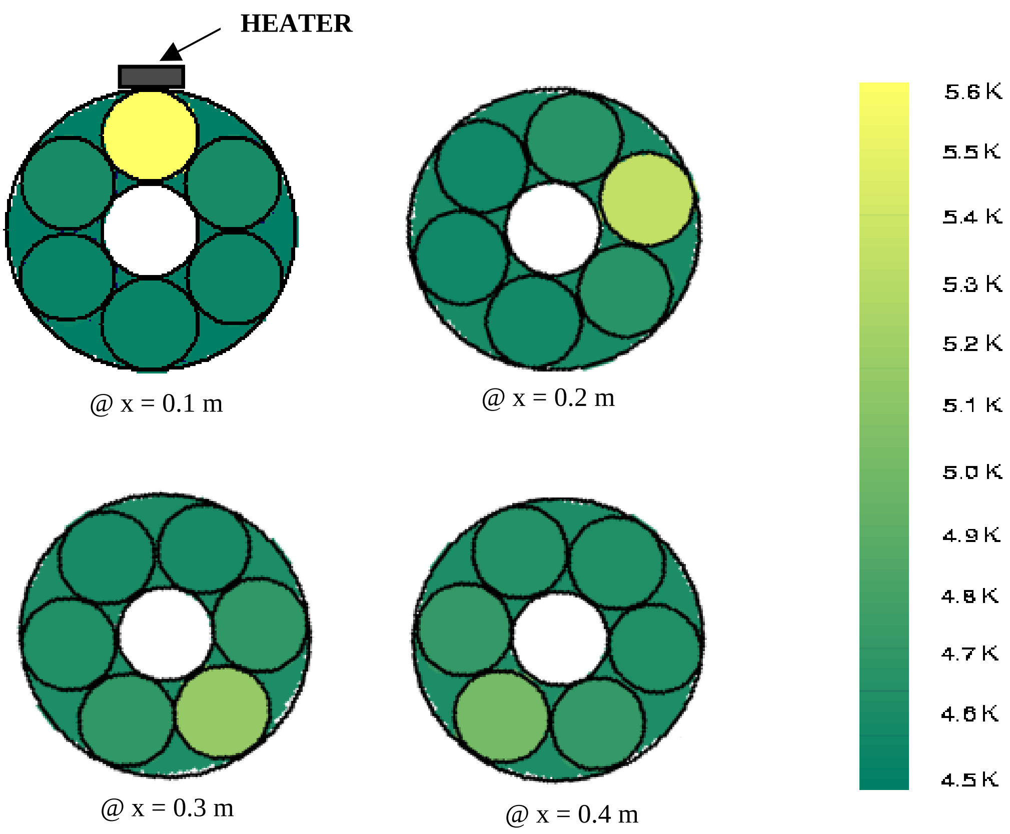

FIG. 4. Quasi-3D steady-state helium temperature distribution computed with M&M in a short CICC sample. Sketches of the conductor cross-section are shown at different positions x along its length. A 0.05 m long resistive heater is applied near x = 0 m on top of the 0.5 m long CICC, in such a way that it locally and directly heats essentially only the helium in the sub-channel (last-but-one stage of the cabling) below the heater. The central channel was closed in this experiment. Moving downstream along the conductor (i.e., for increasing x), heat conduction through the wrapping, which delimits the 6 sub-channels, and convection through the open spaces of the wrapping, lead to temperature equipartition over the cross section of the CICC, while conduction/convection along the twisted sub-channels give the "rotation" of the peak temperature. See also [11] for details.

density is supposed to be uniformly distributed among the strands, for the sake of simplicity. The accuracy of the results obtained (see the references) indicates a posteriori that this assumption is justified in a number of situations. However, there are phenomena (e.g., ramp-rate limitation) and regions (e.g., the joints) where this is certainly not true, and the stability of a conductor may strongly depend on the actual current non-uniformity inside it. While most of the original electromagnetic modeling did not include thermal-hydraulic features, and the vice-versa was also true, several efforts have been made very recently to couple electromagnetic and thermal-hydraulic models, see, e.g., [16]. It is to be expected that more development and validation work will be performed on this subject in the future.

5. Conclusions

The development of thermal-hydraulic models and codes for the analysis of superconducting magnets for nuclear fusion applications is reaching an acceptable level of maturity, with a few contributions from Politecnico di Torino, e.g., the first validated two-fluid code – Mithrandir [3], and the first multi-conductor model – M&M [11]. International collaboration and participation to dedicated experiments world-wide have allowed a continuous validation and updating of the computational tools, leading to typical accuracies O (0.1 K) in a number of situations characterized by broadly different time scales. Some problems remain open, and possible ways to address them have been discussed.

6. References

[1] TSUJI, H., et al., "Progress of the ITER Central Solenoid Model Coil program", Paper IAEA-CN-77-ITER/4, this Conference.

[2] SALPIETRO, E., et al., "Research and development for the ITER Toroidal Field coils", Paper IAEA-CN-77-ITERP/21, this Conference.

[3] ZANINO, R., et al., "A two-fluid code for the thermohydraulic transient analysis of CICC superconducting magnets", J. Fus. Energy **14** (1995) 25.

[4] ZANINO, R., et al., "A comparison between 1- and 2-fluid simulations of the QUELL conductor", IEEE Trans. Appl. Supercond. **7** (1997) 493.

[5] ZANINO, R., et al., "Computer simulation of quench propagation in QUELL", Adv. Cryo. Eng. **43** (1998) 181.

[6] BOTTURA, L., “A numerical model for the simulation of quench in the ITER magnets”, J. Comput. Phys. **125** (1996) 26.

[7] ZANINO, R., MARINUCCI, C., "Heat slug propagation in QUELL. Part I: Experimental setup and 1-fluid GANDALF analysis", Cryogenics **39** (1999) 585; ZANINO, R., MARINUCCI, C., "Heat slug propagation in QUELL. Part II: 2-fluid MITHRANDIR analysis", Cryogenics **39** (1999) 595.

[8] BOTTURA, L., ROSSO, C., “Hydraulic network simulator model”, Internal Cryosoft Note, CRYO/97/004 (1997).

[9] SAVOLDI, L., et al., "Simulation of thermal-hydraulic transients in two-channel CICC with self-consistent boundary conditions", Adv. Cryo. Eng. **45** (2000) 697.

[10] ZANINO, R., et al., "Joint + conductor thermal-hydraulic experiment and analysis on the Full Size Joint Sample using MITHRANDIR 2.1", IEEE Trans. Appl. Supercond. **10** (2000) 1110.

[11] SAVOLDI, L., ZANINO, R., "M&M: Multi-conductor Mithrandir code for the simulation of thermal-hydraulic transients in superconducting magnets", Cryogenics **40** (2000) 179.

[12] ZANINO, R., SAVOLDI, L., "Tests and modeling of heat generation and heat exchange in the Full Size Joint Sample", presented at the 18-th International Cryogenic Engineering Conference (ICEC18), Mumbai, India, 21-25 February, 2000; SAVOLDI, L., et al., "Tests and simulation of thermal-hydraulic transients in the US Prototype joint sample", accepted for publication in Int. J. Mod. Phys. B (2000).

[13] SAVOLDI, L., ZANINO, R., "Analysis of Tcs measurement in conductor 1A of the ITER Central Solenoid Model Coil using the M&M code", presented at CHATS00, Frascati, Italy, September 6-8, 2000. Submitted to Cryogenics (2000).

[14] SAVOLDI, L., ZANINO, R., "Predictive study of current sharing temperature test in the Toroidal Field Model Coil without LCT coil using the M&M code", presented at CHATS00, Frascati, Italy, September 6-8, 2000. Submitted to Cryogenics (2000).

[15] ZANINO, R., et al., "Friction factor correlation with application to the central cooling channel of cable-in-conduit super-conductors for fusion magnets", IEEE Trans. Appl. Supercond. **10** (2000) 1066.

[16] EGOROV, S.A., et al., “Up-grade of the CICC stability analysis taking into account a current imbalance between strands in multistage cables”, IEEE Trans. Appl. Supercond. **10** (2000) 1098; MITCHELL, N., “Non-uniform current diffusion in super- and normal-conducting cables”, presented at CHATS00, Frascati, Italy, September 6-8, 2000. Submitted to Cryogenics (2000).