Two-channel analysis of QUELL experimental results

Luca Bottura, Claudio Marinucci and Cristina Rosso

Abstract— **We have improved the model presently used in the thermo-hydraulic code Gandalf, adapting it to cable-in-conduit conductors with central cooling channel such as those developed for the model coils of ITER. In particular the helium flow in an arbitrary number of parallel channels have now independent velocity and thermodynamic state (pressure and temperature). We demonstrate the capability of the new model by means of comparison to measurements taken during the QUELL experiment in SULTAN. We compare in particular data on heat slug at zero current and field in a broad range of energy inputs, as well as data on quench propagation, to simulation results obtained with the single channel approximation and the newly implemented two-channel model. The latter achieves a significantly better agreement with experimental data, in particular in the case of slow heating transients such as in heat slug propagation tests.**

Index Terms— **Cable-in-conduit conductors, thermo-hydraulic characteristics, dual channel cooling**

I. INTRODUCTION

The computer code Gandalf [1] for the thermo-hydraulic analysis of cooling, quench and stability of cable-in-conduit conductors (CICC's) has been extensively used in the interpretation of the experimental results produced by the QUELL experiment [2,3]. One of the major results of this work was that the code is able to reproduce general scaling and overall behaviour of the relevant parameters such as normal zone length, resistive voltage, maximum cable temperature and maximum pressure with an accuracy that is acceptable for design purposes. At the same time the detailed comparison of the experimental traces and computer simulation with Gandalf has shown that a significant discrepancy was still present on temperature traces especially when slow transients were considered, e.g., heat slug propagation experiments. The time scale of these transients is expected to be the same during pulsed heating and re-cooling phases in the CICC with central cooling channel manufactured for the International Thermonuclear Experimental Reactor (ITER). Gandalf was originally developed with the ITER application in mind as its primary objective. This required a model of a CICC with at least two helium flow channels, such as the interstitial space of the cable bundle and the central cooling channel (hole). The cable model as used in Gandalf up to version 1.8 had independent flow conditions (velocity), but was limited to identical thermodynamic state in the two helium channels, i.e., the same temperature and pressure. This difference is probably due to the simplifying assumption of a single helium state in the cooling channels, as shown by comparison of the 1-fluid model [4] with the 2-fluid model [5]. Following the development of our model [6], we have augmented the capabilities of Gandalf to treat fully independent parallel flows of helium coupled through heat and mass transport at their interface. We describe in this paper the features of the new model and the results of the validation against the QUELL experimental data already used in [2].

Luca Bottura is with CERN, Div. LHC-MTA, CH-1211 Geneva 23, Switzerland. (Luca.Bottura@cern.ch). Claudio Marinucci with EPFL, CRPP, Fusion Technology Div., CH-5232 Villigen PSI, Switzerland (Claudio.Marinucci@psi.ch) and Cristina Rosso with CryoSoft, F-01710 Thoiry, France (CryoSoft@geocities.com).

II. MODEL IN GANDALF 2.0

In order to augment the modelling capabilities of Gandalf we have considered the general case of a superconducting cable with an arbitrary number of parallel flow channels enclosed in a structural jacket, as already discussed in [6] and shown schematically in Fig. 1. The flow in the channels is single phase helium (supercritical or superfluid) dominated by the 1-D component in the direction of the cable length. As customary in pipe flow analysis, we have modelled the viscous forces and the heat transfer through experimental friction factor and heat transfer coefficient correlations. Although work is in progress to modify the thermal and electrical description of the cable and jacket [6,7], we limit ourselves here to a description of the treatment of the helium channels.

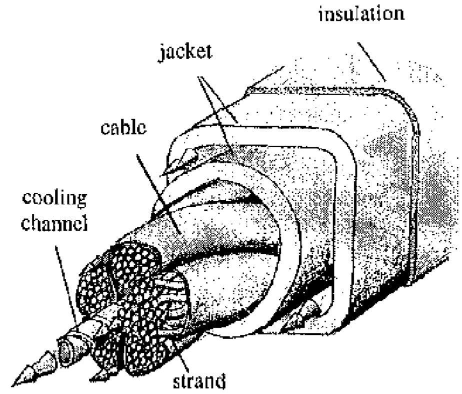

Figure 1. Sketch of the improved cable model implemented in Gandalf showing schematically a superconducting cable and an insulated jacket cooled by an arbitrary number of parallel helium flow channels (arrows).

The cable and jacket are described by the same equations reported in [1] and [6], omitted here for simplicity. Under the above hypotheses, the mass, momentum and energy conservation equations for each channel h can be written in conservative form as follows:

$$A_h \frac{\partial \rho_h}{\partial t} + \frac{\partial A_h \rho_h v_h}{\partial x} = -\Gamma^{\rho}_{hk} \quad (1)$$

$$A_h \frac{\partial \rho_h v_h}{\partial t} + \frac{\partial A_h \rho_h v_h^2}{\partial x} + A_h \frac{\partial p_h}{\partial x} = -A_h F_h - \Gamma^{v}_{hk} \quad (2)$$

$$A_h \frac{\partial \rho_h e_h}{\partial t} + \frac{\partial A_h \rho_h e_h v_h}{\partial x} + \frac{\partial A_h p_h v_h}{\partial x} = -\Gamma^{e}_{hk} + \dot{q}'_h + \dot{q}'_{cf,h} \quad (3)$$

where A_h is the cross section of the channel, ρ_h, v_h, e_h and p_h are the density, velocity, specific total energy and pressure of the helium in the channel. Note that in the above equations we allow an arbitrary variation of the channel cross section and properties along the length. The quantity F_h is the friction force defined using the friction factor f_h and the hydraulic diameter D_h as:

$$F_h = 2\rho_h \frac{f_h}{D_h} v_h |v_h| \quad (4)$$

The friction factor is obtained through experimental correlations that must be adjusted to the conditions analysed. The quantities Γ^{ρ}_{hk}, Γ^{v}_{hk} and Γ^{e}_{hk} are the distributed sources of mass, momentum and stagnation enthalpy per unit length of channel, originating from expulsion (or injection) of helium into (or from) another channel with index k. The convention assumed is that the fluxes are positive if they correspond to a net mass flow from channel h to channel k. We indicate with v_{hk} the transverse velocity from channel h to channel k, and we assume that the two channels have a boundary delimited by a perimeter p_{hk} of which the fraction π_{hk} is perforated. We can write:

$$\Gamma^{\rho}_{hk} = \pi_{hk} p_{hk} v_{hk} \overline{\rho} = \dot{m}_{hk} \quad (5)$$

$$\Gamma^{v}_{hk} = \pi_{hk} p_{hk} v_{hk} \overline{\rho v} = \dot{m}_{hk} \overline{v} \quad (6)$$

$$\Gamma^{e}_{hk} = \pi_{hk} p_{hk} v_{hk} \overline{\rho}\left(\overline{h} + \frac{\overline{v}^2}{2}\right) + p_{hk} h_{hk}(T_h - T_k) = \dot{m}_{hk}\left(\overline{h} + \frac{\overline{v}^2}{2}\right) + p_{hk} h_{hk}(T_h - T_k) \quad (7)$$

where $\dot{m}_{hk}$ is the massflow from channel h to channel k per unit channel length. Quantities with an overline indicate upstream values of the transverse flow (see [6] for details). In Eq. (7) the second term takes into account the fact that energy transfer between the two channels can happen either through mass convection or through heat transfer at the boundary. The heat transfer happens on the interface perimeter p_{hk} with an equivalent heat transfer coefficient h_{hk}. The equivalent heat transfer coefficient between two parallel channels can have a complex form in the case of mixing flows, as in the case of the QUELL cable. The expressions which we have implemented for the mixing h_{hk} were derived by Long [8].

The source term $\dot{q}'_h$ is the heat that enters the channel h per unit length through convection at the wetted perimeter, given by:

$$\dot{q}'_h = \sum_{i=1}^{N} p_{ih} h_{ih} (T_i - T_h) \quad (8)$$

where the sum is over the N solid walls of index i in thermal contact with the channel h, p_{ih} is the wetted perimeter, h_{ih} is the heat transfer coefficient and T_i is the wall temperature (e.g. cable and jacket in [1]). As for the friction factor, the wall heat transfer coefficient is obtained using standard experimental correlations. The term $\dot{q}'_{cf,h}$ is the counterflow heat transport mechanism peculiar to heat transfer in superfluid helium. This term can be written in the form of a non-linear diffusion as discussed in [9].

The above set of equations is a good approximation to the flow in several parallel channels in single phase supercritical or superfluid helium, already proven in several comparisons with experimental data. For the implementation it is more convenient to re-write the system of Eqs. (1)-(3) in non-conservative form. This can be done with trivial mathematics as outlined in [1]. As mentioned above, we have allowed the channel properties to change along the length. This additional feature is useful to model local flow restrictions as present in the coil ends of a force-flow cooled magnet.

III. QUELL EXPERIMENT

The QUench Experiment on Long Length (QUELL) is a thermo-hydraulic experiment specifically designed to produce extrapolation and validation data on an approximately 1:5 scaled down version of the two-channel CICC for the ITER Central Solenoid cable. Figure 2 shows the cross section of the QUELL $(NbTi)_3Sn$ conductor with an outer diameter of 19.4 mm and a central cooling hole of 6 mm inner diameter. The wall at the interface between cable bundle and hole is a spiral tape with a nominal degree of wall perforation of ~14%. The critical current is 32 kA at 4.5 K and 12 T. The QUELL sample is approximately 100 m long, and is well equipped with temperature and voltage sensors, as well as inductive and resistive heaters. The temperature sensors were glued on the Ti-alloy jacket. In the experiments the flow of supercritical helium was from terminal J into the inner layer, the heater sections, the outer layer and out of terminal K (Fig. 2).

The QUELL experiment was performed in the CRPP SULTAN facility. During the test period several types of thermo-hydraulic transients were induced and followed in detail. The transients spanned the whole range of operation of a superconducting coil, from slow pulsed heating and subsequent re-cooling, to fast stability transients followed either by recovery or by a quench. The experimental results produced during the QUELL experiment is the most complete and wide ranging calibration data-base available at the moment for thermo-hydraulic analysis codes, and has been

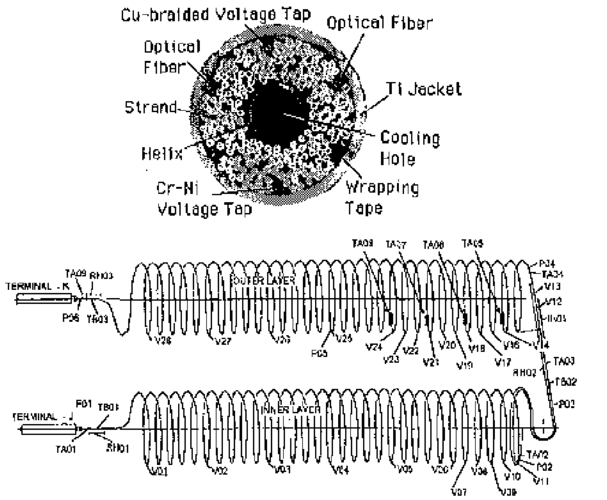

Figure 2. Cross section of the the QUELL conductor (top) and schematic diagram of heater and sensor location along the QUELL sample (bottom). The inductive heater and the resistive heater RH02 are located between inner and outler layer.

extensively used to validate Gandalf (for the results on quench propagation see [2]). In the next section we concentrate on slow heating that proved to be among the most difficult to reproduce and to interpret by numerical simulation

IV. Results

A. Heat slug propagation test

Propagation of a heat slug is a relevant way to assess the thermo-hydraulic characteristics of a CICC with forced flow cooling. The method is based on the observation of how the conductor reacts to the heat input by an external heater, at zero current and magnetic field. The QUELL heat slug propagation tests consisted in: (a) establishing a steady state condition, (b) pulsing one of the heaters with a pre-set energy and (c) recording (among others) the temperature evolution at the thermometers. Two types of heaters were used to deposit energy in the conductor. In the inductively heated runs the heated length was 0.12 m, the heating time 40 ms and the range of energy 39-303 J, 10% of which was directly deposited into the strands and 90% into the jacket. In the resistively heated runs (RH02 heater) these parameters were respectively 2.3 m, 300 ms and 175-1591 J, 100% of which was deposited into the jacket.

Simulations of these tests have focused on 2 inductively heated runs (the heater was operated at 590 Hz) with input energy of 39 J (run 05) and 303 J (run 08), and on 2 resistively heated runs with 175 J (run 09) and 1591 J (run 12). The equivalent mixing heat transfer coefficient between hole and bundle was adjusted to fit the experimental data (i.e., increased by a factor 10) whereas the wall perforation of the hole, as well as all other parameters, was taken from the nominal data set of the conductor. Note that such an increase in the mixing heat transfer is indeed compatible with the

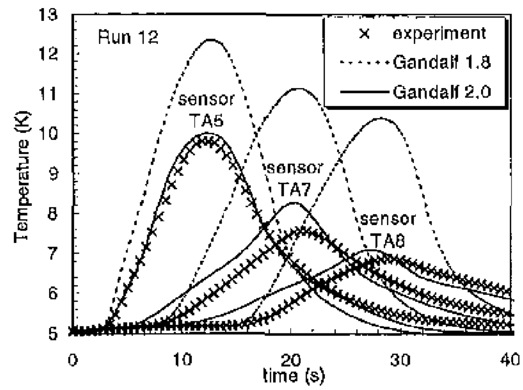

Figure 3. Comparison of measured and calculated temperature traces at several sensors (TA4, TA5, TA7, TA8) downstream of the heater during the heat slug run 12.

expected range of variations discussed by Long [8]. Experimental time histories of helium pressure at inlet and outlet were used as hydraulic boundary conditions in the simulations. The main features of experiment and simulation conditions are described in detail in [4].

Firstly we report the results of a typical heat slug experiment with resistive heater and high energy input (run 12). The agreement between the experimental and the simulated temperatures is good and the improvement introduced by the full two-channel model (Gandalf 2.0) with respect to the single channel approximation (Gandalf 1.8) is remarkable (Fig. 3). The simulated peak temperatures tend slightly to anticipate the experimental values at thermometers downstream of the heater because the simulated helium mass flow is overestimated (see Fig. 4) due to a likely too low friction factor assumed for the central hole. An explanation of this result, as well as of the 'jumpy' behavior of the calculated massflow, is given in [4,5].

The results of all 4 simulated runs are summarized in Fig. 5. To ease the comparison we have taken the maximum temperature increase observed at selected thermometers (crosses), and compared this to the results of simulations performed with Gandalf 1.8 and Gandalf 2.0. The results confirm that the full two-channel model presently available in

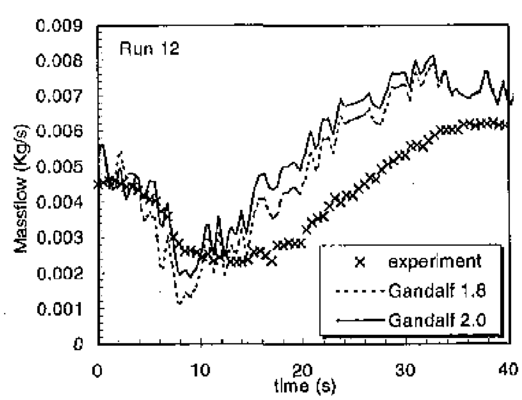

Figure 4. Comparison of measured and calculated massflow at inlet during the heat slug run 12.

Gandalf 2.0 is indeed a significant improvement with respect to the previous approximation.

From the results of these simulations we can justify *a posteriori* our initial speculation on the effect of the separate treatment of the two independent helium streams. One part of the helium flows in the central hole with low hydraulic impedance and large velocity, while another part flows in the interstitial space among the strands with high hydraulic impedance and resulting low velocity. The differential of temperature and velocity between the two flows causes a spread of the original heated slug [8] that thus increases in length and decreases in amplitude, as demonstrated by the measurement and the simulation with Gandalf 2.0.

B. Other validation runs

The model of Gandalf 2.0 was also verified against quench propagation experiments in QUELL. We analysed 4 runs in which the transient was generated by a 1.5 s pulse of the RH02 heater, at different initial and operating conditions (i.e., background magnetic field, current, helium temperature and pressure, corresponding to runs 2, 6, 12 and 13 of [2]). The two-channel model gives a better qualitative and quantitative agreement with the experiment (i.e., resistive voltage, normal zone length and helium pressure at various locations) than the single channel approximation, confirming the results of [2]. In the quench tests the disagreement between Gandalf 2.0 and Gandalf 1.8 is smaller than for the heat slug tests. In fact the higher flow speeds typical of a quench propagation induce a better thermal coupling between bundle and hole through a larger heat transfer coefficient.

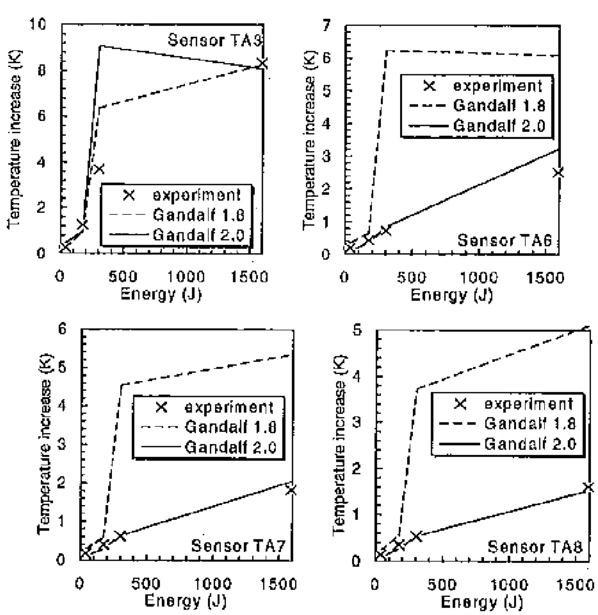

Figure 5. Comparison of measured and calculated maximum temperature increase at several sensors (TA4, TA5, TA7, TA8) for the heat slug tests simulated.

V. Conclusions and Perspectives

We have demonstrated the capability of the new two-channel model, implemented in the computer code Gandalf 2.0, by comparison with measurements taken during the QUELL experiment. The new model:

- achieves a significantly better agreement with experimental data than the single channel approximation, particularly in the case of slow heating transients such as in heat slug propagation tests;
- allows a consistent treatment, i.e. it requires adjustment of only the turbulent heat transient coefficient between hole and bundle but no adjustment in the cable and channel geometry, e.g., the hole wall perforation [5];
- is well adapted to the analysis and interpretation of the forthcoming experiments on the ITER TF and CS model coils with two-channel CICC's.

Work is in progress to improve the model further, implementing an arbitrary number of parallel cooling channels in order to deal with situations in which the coolant speed in the cable space is non homogenous, as observed in an ITER CS model coil conductor test [10].

References

[1] L. Bottura, "A Numerical Model for the Simulation of Quench in the ITER Magnets," *J. Comp. Phys.* **125**, 26-41, 1996

[2] C. Marinucci, L. Bottura, G. Vecsey and R. Zanino, "The QUELL experiment as a validation tool for the numerical code Gandalf," *Cryogenics*, **38**, 5:467-477, 1998

[3] A. Anghel, "QUELL Experiment: Analysis and Interpretation of the Quench Propagation Results"," *Cryogenics*, **38**, 5:459-466, 1998

[4] R. Zanino and C. Marinucci, "Heat slug propagation in QUELL. Part I: Experimental setup and 1-fluid GANDALF analysis", *Cryogenics*, **39**, 7:585-593, 1999

[5] R. Zanino and C. Marinucci, "Heat slug propagation in QUELL. Part II: 2-fluid MITHRANDIR analysis", *Cryogenics*, **39**, 7:595-608, 1999

[6] L. Bottura, 'Modeling Stability in Superconducting Cables," *Physica C*, **310**, 316-326, 1998

[7] L. Bottura, M. Breschi, P. Ribani, 'Electromagnetic Analysis of Current Distribution in Multistrand Cables," Paper presented at 1999 EUCAS, Sitges, Spain

[8] A. Long, "Transverse Heat Transfer in a Cable-in-Conduit Conductor with Central Cooling Channel, Master Thesis, MIT, June 1995

[9] L. Bottura and C. Rosso,"Finite Element Simulation of Steady State and Transient Forced Convection in Superfluid Helium,", *Int. J. Num. Meth. In Fluids*, **30**, 1091-1108, 1999

[10] P. Bruzzone, A.M. Fuchs, V. Vecsey and E. Zapretilina, "Test results for the high field conductor of the ITER Central Solenoid coil," accepted for publication in the Proc. of CEC-ICMC '99, 1999.