TESTS AND SIMULATION OF THERMAL-HYDRAULIC TRANSIENTS IN THE US PROTOTYPE JOINT SAMPLE

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Abstract A limited set of data measured on the US Prototype (USP) joint sample is used to assess the capability of the Mithrandir code to simulate heat-slug transients among the complex assembly of joint components. The Multi-conductor Mithrandir (M&M) code is then applied to simulate heat exchange in a joint of the Central Solenoid Model Coil (CSMC) inner module.

1 Introduction

Joint thermal-hydraulics is an essential ingredient of the analysis of the test program of the International Thermonuclear Experimental Reactor (ITER) model coils (CSMC for the central solenoid [1] and TFMC for the toroidal field magnets [2]), which use dual-channel Nb_3Sn cable-in-conduit conductors (CICC). Indeed, the in-situ measurement of critical properties of the superconductor is foreseen using heaters and sensors *external* to the coil. A proper interpretation of the measurements requires a suitable description of all heat and momentum sources and sinks along the supercritical helium path. In this sense the joint, where heat will be dissipated in, and possibly exchanged through the copper junction between the two CICC, is a particularly critical component.

Within the preparatory work for the CSMC experiment, lap-type joints were developed and tested in the US [3] as prototypes for the joints in the CSMC inner module (the outer module being equipped with butt-type joints developed in Japan). Although the main emphasis of the tests was obviously on the electromagnetic analysis, a limited subset of the data can also be used for thermal-hydraulic studies (zero current tests). Here we describe the experimental setup for the test of the US prototype (USP) joint sample and apply the codes MITHRANDIR 2.1 [4] and the recently developed Multi-conductor Mithrandir (M&M) [5] to the analysis of some selected USP shots. The validated tools are then applied to the study of heat exchange between the two half-joints in selected conductors of the CSMC.

2 Experimental setup and tests

The tests of the USP were performed in 1998 at the Pulsed Test Facility (PTF) of the Plasma Science and Fusion Center (PSFC) of the Massachusetts Institute of Technology (MIT) in Cambridge (MA) USA.

The essentials of the experimental setup are sketched in Fig.1.

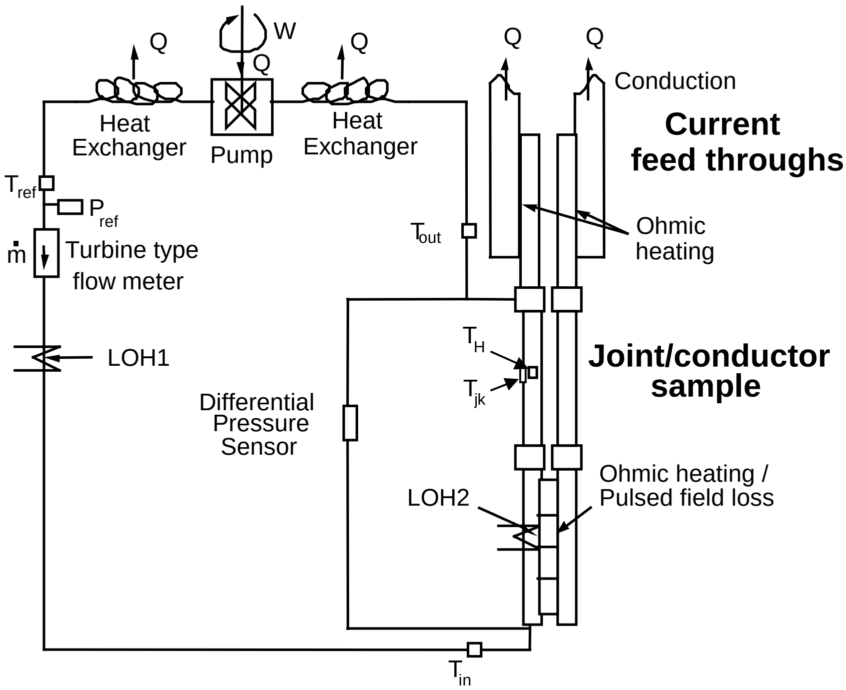

Figure 1: Simplified schematic of PTF supercritical helium circuit during US prototype sample testing (reproduced from [6]). Only the helium line feeding the left leg is shown, although a symmetric helium line is used for the right leg.

Two heaters are available in each leg (L = left, R = right): the first (LOH1 and ROH1) are located about 2 m upstream of the joint inlet, the second (LOH2 and ROH2) are embedded within the joint terminal ~ 0.5m long, along the outer surface of the cable. The available diagnostics for assessment of the boundary conditions in input, and for code validation in output, include in each leg:

- Reference pressure sensor p_{ref}, reference temperature sensor T_{ref} and inlet mass flow meter $(dm/dt)_{in}$, all upstream of ROH1, LOH1, about 3.5 m from joint inlet
- Inlet temperature sensor T_{in}, mounted on the inlet pipe about 1 m upstream from joint inlet

- Sample temperature sensors – T_{jk} in the conductor jacket, and T_H *in the central channel*, at the same axial location about 1.7 m downstream from joint inlet. (Notice that the latter sensor provides the first data for validation of thermal-hydraulic codes against helium temperature in the hole for dual channel CICC. In QUELL [7], e.g., only the jacket temperature signal was both available and reliable)
- Outlet temperature sensor T_{out} (mounted on the pipe coming out at 90 degrees from the conductor, about 0.1 m downstream of the bifurcation, see Fig.1), and differential pressure sensor Δp (between the same location and the joint inlet).

Among the large set of USP experimental shots we select here the two most representative for the purpose of our thermal-hydraulic analysis, see Table I: the first is heated upstream of the joint, the second on the joint.

Shot #	p_{in} (Pa)	T_{in} @ t=0 (K)	Heater	Q (W) [&]	τ (s) [$]
980205003	6.1e5	4.4	(L/R)OH1	45	5
980203044	4.9e5	4.5	(L/R)OH2	20	20

[&] Input power in the heater
[$] Time duration of the heating (square wave)

Table I. Major features of USP shots analyzed by MITHRANDIR 2.1 and M&M. All shots have a nominal mass flow rate of ~ 4.8 g/s/leg. Notice that the input power is symmetrical in both legs.

3 Results of simulations

3.1 Code validation against USP data

The major features of these simulations are as follows:

- We simulate the joint+conductor system up to the radial exit from the conductor
- Only the left leg is simulated since the heating is symmetrical
- The experimental T_{in} is imposed at the inlet, together with constant helium speed both in hole and bundle region (we assume that the small mass flow rate variation during the transient is due only to density variation [4]). In the case of the upstream heated shot we neglect the deformation of the inlet temperature profile (decrease in peak value, increase in width), due to heat diffusion in the SS inlet pipe. (The results of a more sophisticated simulation, which includes the inlet pipe and the heater, show however a small deformation)
- For the friction factor a constant f_H = 0.025 has been assumed in the central channel (approximated from friction data collected previously for this type of spiral at MIT and CEA Cadarache, France), while improved Katheder has been used for the bundle region

- Optimal bundle-hole coupling parameters (effective perforated fraction F = 0.05 of the spiral, heat transfer coefficient multiplier H_{nowall} = −10 through the perforation) [4] have been calibrated to reproduce shot # 980205003, and they have been kept frozen for shot # 980203044
- In the output the temperature at T_{out} has been computed from the (hole + bundle) average enthalpy of the outlet helium flow.

The results of the analysis are reported in Figs.2a, b. In Fig.2a it can be noticed that the originally narrow pulse (3s) is already spread out (~ 5-10s) at the joint inlet, and it broadens further while proceeding downstream. T_H anticipates T_{jk} because the latter is tightly coupled with the bundle helium, which flows slower. Overestimation of T_{out} is probably related to conduction heat losses to the terminal (see Fig.1), which are not included in the model. Similar features appear in Fig.2b although here the broad profiles are mostly due to the originally broad (20s) heat pulse. The accuracy of the computed results appears in both cases to be good. A parametric study of the effects on T_H of variation of hole friction factor and of the perforated fraction between hole and bundle has been performed for shot # 980205003. The

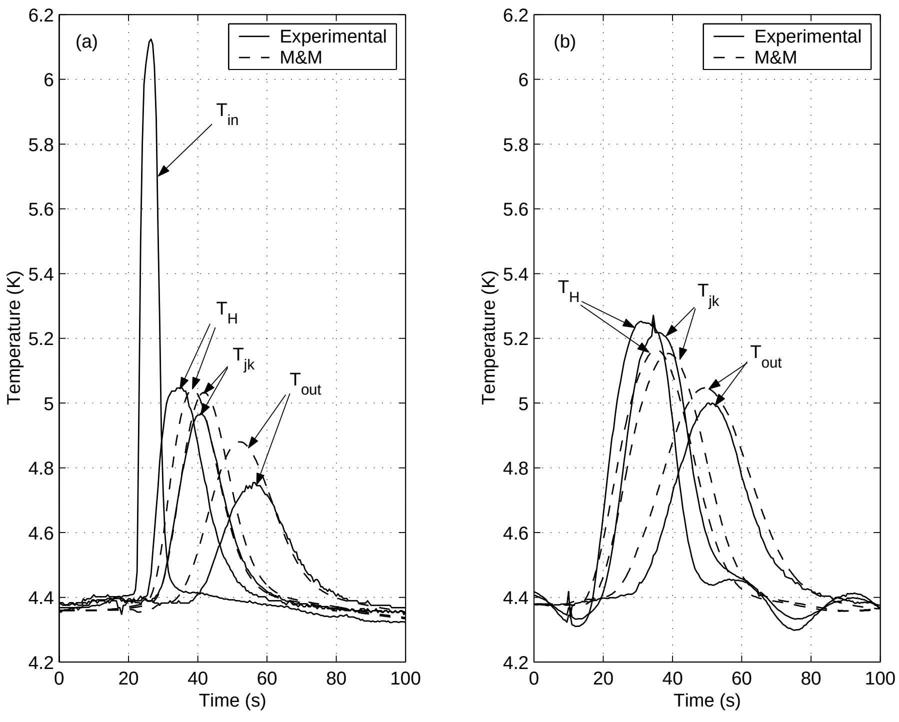

Figure 2: USP shot # 980205003 (a) and 98020344 (b). Temperature profiles computed at different sensors with M&M (dashed) are compared with the experimental data (solid). In the right subplot T_{in} = 4.5K = constant.

sensitivity of the computed results to changes in the values of these parameters is relatively small (~ 0.1K in peak temperature and ~ few s in phase for a factor of 3-5 difference in parameters, not shown).

3.2 Analysis of heat exchange in a CSMC inner module joint

The M&M code has already been validated in the past [5] against heat exchange in the Full Size Joint Sample (FSJS) for the TFMC. Unfortunately, no USP shots are available with asymmetrical conditions in the two legs (which would have led to heat exchange between the two half-joints). This situation, however, occurs in practice during the tests of the CSMC, e.g., at the inlet joint between conductor 1B and busbar, or between externally-heated and non-externally-heated conductors, e.g., 2A and 3B, or else at the outlet joints between conductors at different temperature, e.g., 1A and 2A. Since the only available temperature signals in the model coil are upstream of the inlet joints and downstream of the outlet, the assessment of heat exchange in the joints is relevant for deducing the temperature profile along the conductors.

Fortunately, very recent data from the first CSMC tests already allow a limited study of heat exchange in the CSMC inner module joints using M&M, and here we shall consider in particular the case of the inlet joint between conductor 1B and busbar. The results computed for different inlet temperatures in the heated conductor are summarized in Table II. Notice that, for high inlet temperatures (above 10K) in the heated leg, the predicted temperature drop along the joint can be significant (i.e., well above 1K). This condition should be encountered, e.g., during T_{cs} measurements in layer 1, at current below 30kA, and this variation should be considered in the interpretation of the results of the testing program. The comparison between preliminary experimental data from thermal-hydraulic tests of the CSMC and computed values, made in order to assess the reliability of the prediction, shows that a very good accuracy is obtained.

Conductor 1B (heated)			Busbar (cold)			
dm/dt (g/s)	T_{He} @ joint inlet (K)	Comp. T_{He} @ joint outlet (K)	dm/dt (g/s)	T_{He} @ joint inlet (K)	T_{He} @ joint outlet (K) Comp.	T_{He} @ joint outlet (K) Exp.
4.5	6.5	6.1	10.0	4.3	**4.7**	**4.6**
4.5	10.0	8.6	14.0	4.3	**5.0**	**5.1**
2.0	12.0	8.6	16.2	4.5	**5.3**	**5.2**
2.2	18.5	11.6	17.5	4.5	**5.6**	**5.7**

Table II. Computed heat transfer in the joint between conductor 1B and the busbar in the CSMC. The helium temperature @ the joint outlet is computed for varying inlet temperature in the heated conductor and varying mass flow rate in both heated and non-heated legs. The experimental values are also reported for the sake of comparison. Notice that the experimental values are measured downstream of a further joint (not considered here) between the busbar and conductor 18A. This is downstream of the joint considered here, and may possibly lead to a decrease of the outlet helium temperature.

4 Conclusion and perspective

Good accuracy is obtained between the results of the Mithrandir code and those of a limited set of thermal-hydraulic tests of the USP joint, with errors ~ 0.1K in temperature and ~ few s in phase. A first comparison against CSMC data confirms this result. This study contributes to the essential step of validation of the computational tools, which are now being applied to the analysis of the CSMC and TFMC test programs.

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