Joint + conductor thermal-hydraulic experiment and analysis on the Full Size Joint Sample using MITHRANDIR 2.1

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***Abstract* – Accurate modeling of thermal-hydraulic transients in a joint + conductor system, e.g., in the analysis of the test program of the ITER Model Coils (CSMC and TFMC) requires a major extension of existing codes. The two-fluid MITHRANDIR code has been upgraded accordingly to version 2.1 and it can now deal with variable geometry and materials along the hydraulic path. A limited validation of the extended quasi one-dimensional model is presented against data we obtained in dedicated thermal-hydraulic tests on the Full Size Joint Sample (FSJS). Taking into account experimental uncertainties the agreement between prediction and measurement can be considered good.**

I. INTRODUCTION

The Toroidal Field Model Coil (TFMC) [1] and the Central Solenoid Model Coil (CSMC) [2] are to be tested at FZ Karlsruhe, Germany, and at JAERI Naka, Japan, respectively, within the frame of the International Thermonuclear Experimental Reactor (ITER) program. In the TFMC, an experimental evaluation of the Nb_3Sn super-conductor critical properties is foreseen by heating the helium upstream of an (inner) joint, which electrically connects adjacent pancakes on the same radial plate. If the heating is transient, a heat slug propagates through the joint, and downstream to the high field region of the dual channel cable-in-conduit conductor, where a quench could be initiated. A somewhat similar (but DC) situation, *mutatis mutandis*, will be encountered in the test program of the CSMC. If this strategy works or not, will depend among others on the possibly delicate balance between critical properties of joint vs. conductor, and magnetic field dependence of the current sharing temperature [3].

In the joint several parameters are different from those of the conductor (materials, geometry) and this contrasts with the assumption of uniform properties along the length made in all existing thermal-hydraulic codes, e.g., the two-fluid code MITHRANDIR [4]. The simultaneous treatment of joint + conductor requires therefore a major extension of the codes.

Recently, we have studied experimentally the basic configuration of a twin-box joint connecting two relatively short (~ 3m long) conductors in a series of dedicated thermal-hydraulic tests on the Full Size Joint Sample (FSJS) experiment, designed at CEA Cadarache, France, and performed in the CRPP SULTAN facility at Villigen PSI, Switzerland [5]. These constitute actually three separate tests of different joint + conductor couples: SS-FSJS, TFMC-FSJS and TF-FSJS [5]. Here we shall concentrate on the SS-FSJS, which was the first one to be tested (December 1998). The TFMC-FSJS was tested in July 1999, the TF-FSJS in September 1999.

As a first attempt in the direction discussed above, we present here an extension of the MITHRANDIR code which allows the simultaneous treatment of joint + conductor. The model is validated against a limited set of data from the SS-FSJS experiment, obtained for different external heating scenarios.

II. MODEL UPGRADE

The model implemented in the previous version of MITHRANDIR has been extended in two major respects. Sketchily, we can now allow, *along the hydraulic path*:

- Variable cross section of helium passage in the cable bundle region and in the central channel (hole);
- Variable material and geometrical parameters (e.g., jacket composition and cross section, central tube-helix perforation and thickness, super-conductor properties, cable void fraction, contact perimeters, etc.).

Discontinuous variations are allowed in principle, except in the helium cross-sections. For the latter, the model retains a quasi one-dimensional nature, i.e., the length scale of variations along the conductor cannot go below a few hydraulic diameters [6]. Actual discontinuities in the design (e.g., the change in the hole cross section at the end of the joint, see Fig. 1) are approximated by linear variations over distances sufficiently short to reproduce semi-quantitatively the real geometry. The most significant *localized* head loss, i.e., at joint outlet, was semi-quantitatively simulated by an artificial enhancement of the local hole friction factor.

Of course, it must be observed that the actual geometry of, and the flow in a joint (see below) are three-dimensional, and as such a quasi one-dimensional model as the present one constitutes only a first approximation. In CICC thermal-hydraulics, however, the relative accuracy and computational cost of a 1-D solution have been shown in the past to be already significant [7],[8]. Although interesting in principle, higher dimensional *flow* models are essentially unpractical, while higher dimensional *solid* models are not mandatory. Indeed, although much less elongated than the conductor, the joint still has a ratio of transversal to axial dimensions ~ 1/10, and we assume the jacket to be adiabatic, i.e., the error in a 1D treatment of heat conduction should not be large even in this case.

III. SS-FSJS THERMAL HYDRAULIC TESTS

In the present paper we shall concentrate on the SS-FSJS set of thermal-hydraulic (TH) experiments. The joint geometry, which was studied in this case, is shown in Fig. 1. This joint is considered fully representative of the TFMC inner joint.

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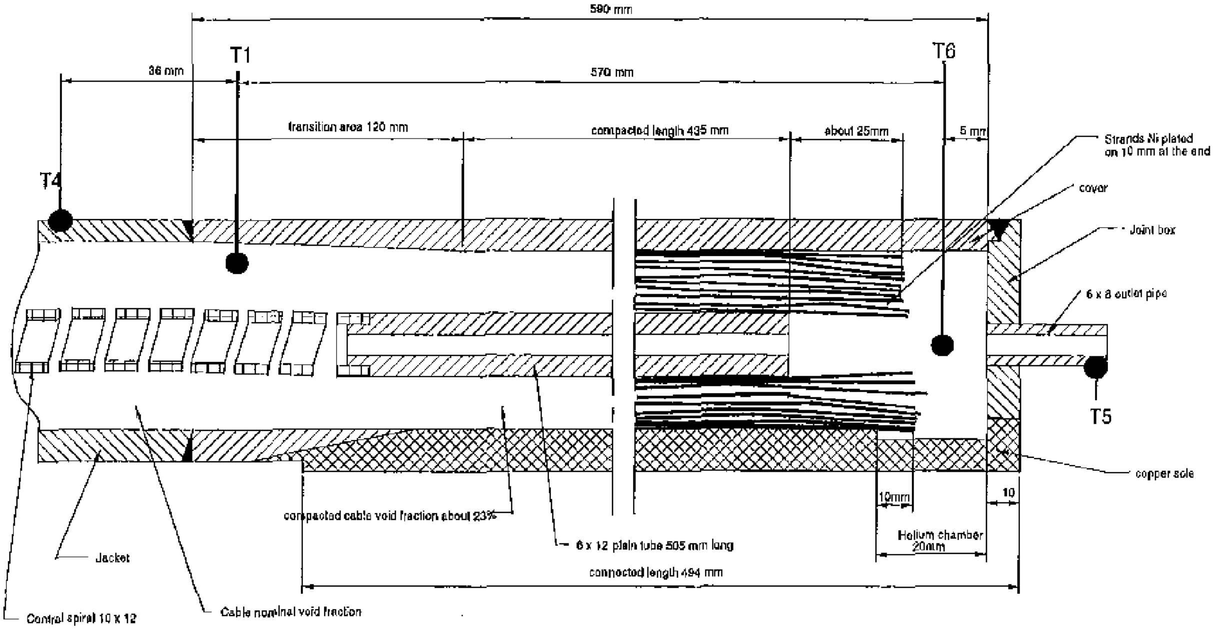

Fig. 1. Schematic view of the SS-FSJS half joint (Courtesy of P. Decool). The other conductor and half joint are located symmetrically with respect to the lower horizontal boundary. In the thermal-hydraulic tests He flows from right to left.

However, a major TH difference is the "praying hands" concept, compared to the "shaking hands" foreseen for the TFMC.

The hydraulic circuit setup is shown in Fig. 2. For the TH experiments, the He flow is reversed with respect to the electromagnetic tests, in order to better, although not completely (see above) approach the situation in the TFMC [9]. Helium enters the system from the bottom (the right-hand side in Fig. 1), flowing first through the two half-joints (as in a co-current heat exchanger, while flow in the TFMC joints will be counter-current), and then into the two conductor legs. Two resistive heaters (LH, RH) are positioned a few meters upstream of the joints and used as drivers for the transients. (However, only the signal from the heater on the right leg was recorded.) Heating up-and-down steps, heat slugs, steady state measurements of thermal coupling between the two half joints, current up-and-down ramps, have been performed for different mass flow rates. Furthermore, when using the resistive heaters, symmetrical and nonsymmetrical heating of the two legs has been tested [9].

Temperature sensors were positioned in each half-joint as shown in Fig. 1, and in each leg (R=right, L=left) of the conductor. (Offsets between these sensors [9] have been eliminated, attributing them to steady-state heat sinks which are not included in our model.) Of particular relevance for our validation will be:

- the T6 sensor, measuring the temperature of the He in the mixing chamber at the joint entrance, where T_B (bundle He temperature) ~ T_H (hole He temperature),
- the T1 sensor, measuring T_B at the exit of the joint,
- the T3 sensor, measuring the jacket temperature T_{jk} in the conductor, about half a meter downstream from the joint exit.

Pressure and mass flow were measured several meters from the conductor exit, but only the Venturi on the left leg (LV) was properly working.

IV. MODEL VALIDATION AGAINST SS-FSJS DATA

For validation purposes we shall concentrate here on a very limited subset of the thermal-hydraulic tests described above. For the present the analysis is restricted to runs:

a) with *no current*, i.e., no heat is produced in the joint,

b) *symmetrically heated*, i.e., in principle (see below) without heat exchange between the two half joints.

Three different runs have been selected, as representative of the two heating scenarios used in the tests:

1) a series of up-and-down steps (exp. run # E12-17-018),

2) two heat slug runs (exp. run # E12-17-008, 002).

The first type of run is a DC pulse obtained switching on the

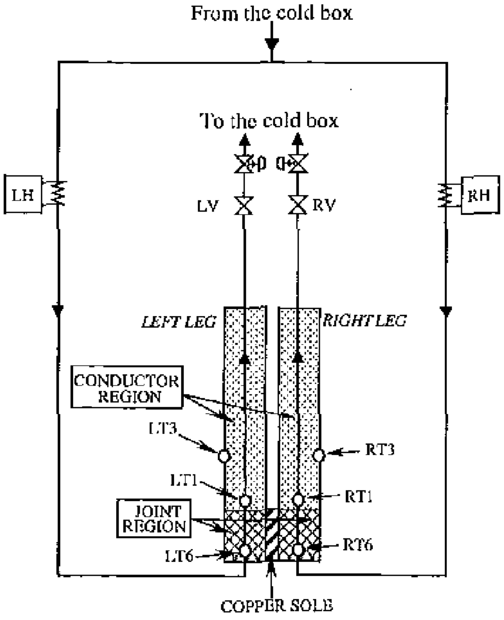

Fig. 2. Sketch of the SS-FSJS hydraulic circuit configuration (thermal-hydraulic tests only)

TABLE I

INPUT PARAMETER VARIATION ALONG THE CONDUCTOR

	Location (mm) (a)	D (b)	t (c)	void (d)	A_{jk} (e)	Cu_{jk} (f)	F (g)	$P_{St\text{-}He}$ (h)	$P_{Jk\text{-}He}$ (i)
Mixing chamber	$0 < x < 15$	6.e-3	3e-3	0.23	2371.e-6	0.29	1.	1/2	1/4
Joint	$15 < x < 535$	6.e-3	3e-3	0.23	2371.e-6	0.29	0.	1/2	1/4
Conductor	$535 < x < 1151$	10.e-3	1e-3	0.361	1434.e-6	0.	0.005	5/6	3/4

(a) Linear variations are assumed on a length of a few hydraulic diameters around the given location
(b) Inner hole diameter (m), (c) Tube thickness (m), (d) Cable space void fraction
(e) Jacket cross section (m^2), (f) Copper fraction in the jacket (a homogeneous mixture of Cu and SS is assumed in the joint)
(g) Effective perforated fraction between hole and bundle (free fitting parameter in conductor)
(h) Fraction of strand perimeter in contact with He (guessed), (i) Fraction of jacket perimeter in contact with He (guessed)

heaters and keeping them on for as long a time as sufficient for the system to reach a new steady state. The second one is a transient pulse obtained by turning the heaters on (~ 70W) for a limited time (~ 10 s and ~ 6 s, respectively) shorter than the typical time scales of the system. This type of transient, often used for experimental thermal-hydraulic assessments of CICC, has been thoroughly analyzed very recently for the case of the QUELL conductor [7]. The first type of run could be relevant to the CSMC test program, where heat slugs are for the moment not foreseen, whereas the second should be relevant to the TFMC.

In both cases the same set of input parameters of MITHRANDIR was used, a summary of which is given in Table I (compare with Fig. 1 and see also [9] for details). Bundle-hole coupling parameters [10] were chosen to get good accuracy for the up-and-down steps, and then kept fixed.

A. Boundary conditions: It results from Section III that there are not enough data to attempt a simulation of a single leg *including the heaters and the connecting pipe* to the joint. We shall therefore use the time dependent signal at T6 as one of the inlet boundary conditions, and attempt a prediction of the evolution of the T1 and T3 traces. (Notice also that our computational domain starts at T6 and ends at T3). Finally, we shall concentrate on the left leg, where at least the far outlet mass flow rate signal is available.

Even using the above strategy it is impossible to reconstruct with the available data a full set of mathematically sufficient boundary conditions, because we lack the inlet pressure and/or the inlet mass flow. Imposing a fixed inlet pressure computed from steady state information leads to significant disagreement with the experiment. An ad-hoc stratagem has therefore been developed and used to partly overcome this limitation. In essence, analysis of the mass flow signal at the far outlet of the left leg has shown that its time dependence was mainly due to temperature dependent density variations, whereas the outlet flow speed is much more constant during the transient. We have therefore assumed that the *inlet* flow speed is approximately constant, and adjusted the couple V_B and V_H until we obtained a steady state mass flow at outlet, approximately matching the measured one, and equal pressures at joint inlet. Notice however that, as mentioned above, the location of the computational outlet and that of the flow meter are different, i.e., some heat loss is likely to occur between the two, and a time lag is expected to exist between the two signals during the transient. Taking all this into account, the *transient* outlet mass flow is reasonably reproduced by the model, see Fig. 3.

B. Analysis of up-and-down steps: In this case the power in the heaters was first increased in three steps (10 W, 30 W, 50W), and then brought back to zero in a single step. The resulting transient at the 3 temperature sensors is reported in Fig. 4, separately for each of the steps (notice that the initial and final temperatures of each step are essentially fixed). The different slopes of the T1 and T3 experimental signals with respect to T6 show the influence of conduction in the solids and heat exchange between bundle and hole, in comparison to rigid convection. One sees that, except for a somewhat earlier start of the computed signals, the agreement with the experiment is very good. Notice also that the differences are very small in absolute terms (~ 0.01K).

Also the possible effects of different effective perforated fraction F of the helix delimiting the conductor hole – a free fitting parameter of the model [4] – have been assessed for the up-and-down steps. We chose F = 0.005 (see Table I) so as to give a good agreement, while relatively significant differences arise in the computed signals for much smaller or much larger F.

C. Analysis of heat slugs: Two heat slug runs were simulated, as shown in Fig. 5, which collects experimental and computed signals at the three temperature sensors, as a function of time. It can be noticed that the overall agreement between computation and experiment is reasonable, with average differences ~ 5% if normalized to the temperature itself. The major noticeable disagreement appears in a global overestimate, O (0.1K), of the T1 signal, which could be related to an underestimate of other heat transport mechanisms in the joint, besides He convection in the bundle. The agreement in the T3 signal is good, although the simulated peak trails the experiment. Concerning these inaccuracies it should however be noticed that, besides the already mentioned difficulties with boundary conditions, additional experimental uncertainties are present. For instance, in the case of Fig. 5a, although nominally symmetrically heated, about 0.5K difference appears between the peaks of the measured RT6 (~ 6.6K) and LT6 (~ 7.1K) signals (not shown), so that heat exchange between the two half-joints cannot be fully ruled out. Furthermore, the LT1 signal trails RT1 by ~ 1s (not shown) so that the actual experimental time needed by the heat slug to reach the joint outlet is not precisely determined.

The spatial profiles of all MITHRANDIR variables, computed at some instant during the transient, are shown in Fig. 6. Notice that

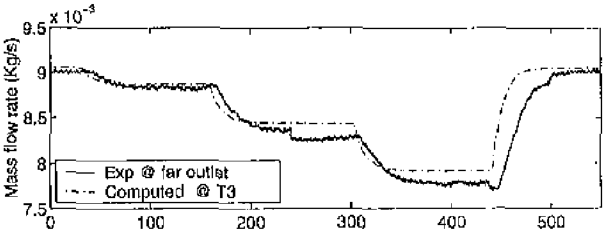

Fig. 3. SS-FSJS run # E12-17-018. Comparison between outlet mass flow rates: measured far downstream from T3, and computed at T3.

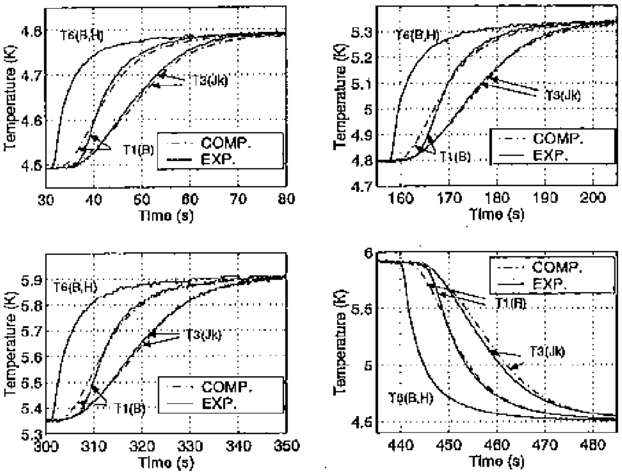

Fig. 4. SS-FSJS run # E12-17-018. Comparison between experimental and computed temperature evolutions: $T_B \sim T_H$ at T6, T_B at T1, T_{jk} at T3.

p_B and p_H can hydraulically decouple only in the unperforated joint region. At the joint/conductor boundary, the effect of increased hole cross section leads to a recovery of p_H, and the finite helix perforation leads again to pressure equipartition (the small pressure oscillations disappear when a finer mesh is used). The profiles of the flow speeds are also very sensitive to the variation in He cross-section. Because of the increased area of passage, and because of the higher friction factor in the conductor hole with respect to the smooth tube in the joint, V_H is much smaller in the conductor than in the joint. On the contrary, V_B decreases at the transition between joint and conductor because of increased void fraction and pressure relief to the hole. The helium temperature profiles show a significant de-coupling between bundle and hole. This is related to the fact that the residence time of the hole He between T6 and T3 is ~ 2s, while the coupling time between hole and bundle is ~ 3-4s. Notice finally that the strands are very well thermally coupled to the bundle He, while temperature differences with the jacket are still typically below 0.2K (the "discontinuity" in T_{jk} is due to the different geometry and material of joint jacket and of conductor jacket, see Table I).

V. CONCLUSION AND PERSPECTIVE

We have performed dedicated thermal-hydraulic tests of the SS-FSJS, and a limited representative subset has been used for a first validation of MITHRANDIR 2.1 for different external heating scenarios (steps and heat slugs). The new model can deal with variable parameters along the hydraulic path, as typical of a joint + conductor system. In view of the number of (even experimental) uncertainties in the problem, the agreement between computed and measured temperature evolution at different locations can be considered good.

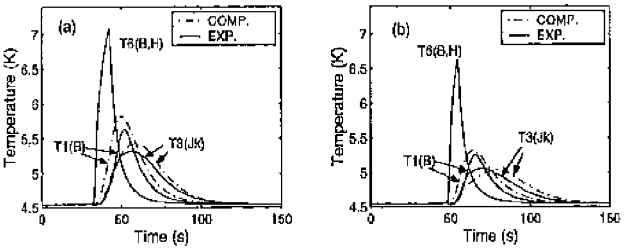

Fig. 5. SS-FSJS runs # E12-17-008 (a) and # E12-17-002 (b). Comparison between experimental and computed temperature evolutions: $T_B \sim T_H$ at T6, T_B at T1, T_{jk} at T3.

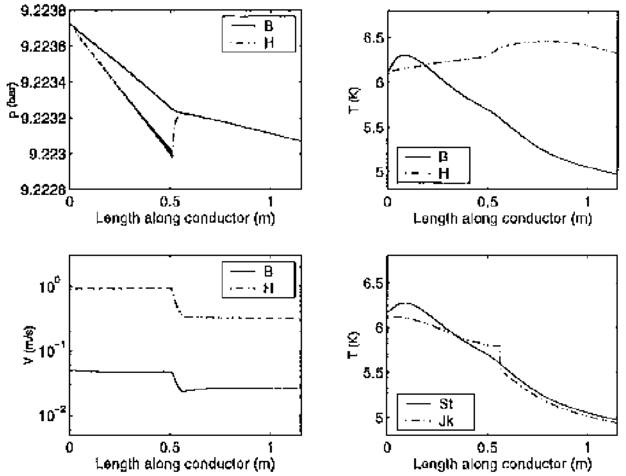

Fig. 6. SS-FSJS run # E12-17-008. Computed spatial profiles at t = 45s: p_B, p_H (a), T_B, T_H (b), V_B, V_H (c), strand temperature T_{St}, T_{jk} (d).

Modeling of heat generation in the joint and heat exchange between the two half-joints, which are needed for a realistic simulation of TFMC conditions, will be discussed elsewhere [11].

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