Pretest analysis of Tcs measurements in the Central Solenoid Model Coil

Roberto Zanino [$], Nicolai Martovetsky [&] and Laura Savoldi [$]

[$] Dipartimento di Energetica, Politecnico, C.so Duca degli Abruzzi 24, I-10129 Torino, Italy.
[&] LLNL, P.O. Box 808, L-641, Livermore, CA, 94551-0808 USA.

Measurement of the current sharing temperature T_{cs} in the Central Solenoid Model Coil (CSMC) [1] will be in some cases indirect, relying only on thermometers at the inlet and outlet of each conductor. Since the temperature profile along each conductor is influenced by heat exchange between adjacent conductors, some model is needed for a proper interpretation of the tests. A simplified steady-state approach, accounting for heat exchange between adjacent conductors is used here, and a set of tests for the calibration of the model is recommended. A qualitative strategy for T_{cs} evaluation is presented for conductors *1A* and *5A*.

1 INTRODUCTION

The CSMC will be tested in 2000 at the JAERI facility in Naka, Japan, in the frame of the International Thermonuclear Experimental Reactor program. The coil is layer-wound two-in-hand with Nb_3Sn 2-channel cable-in-conduit conductors, each approximately 100 m long, cooled by supercritical helium (He). In each of the 18 layers of the coil, conductor *A* is separated from conductor *B* by an epoxy-kapton insulation. A similar, but thicker insulation is used in between adjacent layers, see Fig.1.

In the CSMC testing program [2], T_{cs} should be measured in different conductors by slow increase of the inlet temperature, using resistive heaters. Of course, since the magnetic field varies in the direction x along the conductor, so does $T_{cs}(x)$. Therefore, *the* T_{cs} of a given conductor will be found where its temperature profile $T(x)$ first intersects $T_{cs}(x)$, originating a normal zone to be detected by the voltage sensors. The only available sensors for $T(x)$ in each conductor measure the inlet temperature T_{in}, upstream of the lower joint, and the outlet temperature T_{out}, downstream of the upper joint, while in layers *1* (the innermost one) to *6* the magnetic field reaches its maximum near the middle of the conductor. Since heat exchange takes place between the two conductors of a given layer (inter-turn coupling) and between adjacent layers, some kind of computational tool is needed in order to find $T(x)$. A simplified model is described and applied here to conductors *1A* and *5A*, for which the T_{cs} measurement is foreseen with different heating scenarios. On the contrary, in the layers from *7* outwards, the magnetic field reaches its maximum at the conductor ends, and the temperature measured by the inlet sensor when a transition to the normal state starts can be considered *a priori* a good approximation of T_{cs}.

2 MODEL DESCRIPTION

We want to compute the steady-state profile $T(x)$ in a conductor, taking into account the heat exchange with neighboring conductors (see Fig.1). The analysis performed here relies partly on the model presented in [3]. Joints are neglected, as well as heat conduction in the solids compared to heat convection.

According to [2], we assume given mass flow rate *dm/dt* (4e-3 kg/s in externally heated conductors, 10e-3 kg/s in non-externally-heated conductors). We do not attempt here to accurately represent the coil topology, which is very complicated. In particular, we assume that:

1) In each layer, conductor *A* is coupled with two different turns of conductor *B*, and viceversa, see Fig.1. This *non-local* inter-turn coupling is approximated assuming that the given conductor, say, *1A*, exchanges heat only *locally* with *1B*, through twice the area of the upper (or lower) surface.

2) The inter-layer coupling of, say, *1A*, is averaged locally: for half of its side length with *2A* and for the other half with *2B* (see Fig.1).

For the *i*-th conductor the steady-state power balance is then:

$$(dm/dt)_i\, C_p\, (dT_i/dx) = \sum_{(adj)i} \alpha_{ij}\, (hP)_{ij}\, (T_j - T_i) \qquad (1)$$

where the sum extends to all conductors *j* adjacent to *i*, α_{ij} = 2 for inter-turn and = 1 for inter-layer. Since experimental data are still missing, for the effective heat transfer coefficient *h* and the effective heat transfer perimeter *P* we use for the moment (see below) [3]:

$$1/(hP)_{ij} = 1/(h_{He}P_{He})_i + (\delta_{Jk}/(\kappa_{Jk}\, P_{Jk}))_i + (\delta_{ins}/(\kappa_{ins}\, P_{ins}))_{ij} + (\delta_{Jk}/(\kappa_{Jk}\, P_{Jk}))_j + 1/(h_{He}P_{He})_j \qquad (2)$$

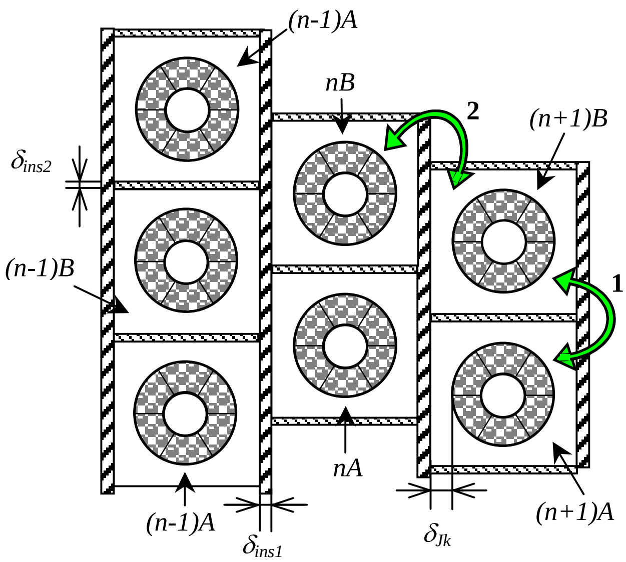

Figure 1 Schematic cross section of 3 adjacent layers (*n-1*, *n*, *n+1*) in the CSMC. Inter-turn (arrow **1**) and inter-layer (arrow **2**) heat exchange takes place between adjacent conductors.

where a series of thermal resistances has been assumed to model the heat exchange, including thermal (convective) boundary layer(s) between He and conductor/jacket (*Jk*), heat conduction through the jacket(s) and heat conduction through the insulation (*ins*). Below we use $(P_{Jk})_{interturn} = d$, $(P_{Jk})_{interlayer} = d/2$, $h_{He}P_{He}$ = 6 W/mK, δ_{Jk} = 7e-3 m, κ_{Jk} = 0.3 W/mK, δ_{ins1} = 6e-3 m (inter-layer) and δ_{ins2} = 3e-3 m (inter-turn), κ_{ins} = 0.12 W/mK [3].

With given co-current mass flow in the parallel conductors, the set of power balances (1) can be solved analytically as an initial value problem, *using only the* T_{in} *as boundary conditions*. We assume that the inlet temperature of the externally heated conductors is always fixed at T_{in}^H = 9 K, while that of the non-externally-heated conductors is always fixed at T_{in}^C = 4 K. In the analysis, additional layers are added subsequently to the externally heated layers (asymmetrically for layer *1* and symmetrically for layers *5-6*, see below), in order to find out at which stage "saturation" (= invariance) of *T(x)* occurs in the most critical (innermost, warmer) conductor. In all layers not included in the analysis at a given stage, *T(x)* is assumed to stay fixed at the respective inlet value T_{in}^C. At the boundary with the fixed temperature conductors we assume adiabatic conditions (however, results at saturation will be independent of this boundary condition).

3 RESULTS AND DISCUSSION

Two cases are considered here [2]:
1) Layer *1* → Externally heated conductors *1A*, *1B*, *2A*, *2B*.
2) Layer *5* → Externally heated conductors *5A*, *6B*.

The computed results are reported in Figs.2a,b for conductor *1A* and *5A*, respectively. As expected, if enough conductors are taken into account, *T(x)* in *1A*, *5A* becomes invariant with respect to the inclusion of other conductors in the power balances (1).

3.1 Analysis of layer *1*

For the sake of simplicity, the conductors in layers *1-3* are assumed to have the same length L_{1-3} = 80 m and square conductor size d_{1-3} = 0.051 m. Fig.2a shows *T*(*x*) in layer *1* in different models. (Both conductors in layer *1* have the same *T(x)*, so only a single conductor per layer has to be analyzed.) Let's assume that only layers *1* and *2* are solved by (1). Since the rest of the layers is thermally insulated from these two layers, and the layer-*2* inlet temperature is also the inlet temperature of layer *1*, a flat *T(x)* is trivially obtained in layer *1* .

Let us include one more layer into the picture – layer *3*, which inlet is not heated, opposite to the layers *1* and *2*. Then a drop of the layer-*1 T(x)* will occur, resulting from heat transfer to the cold layer *3* through layer *2*. Let us add one more layer into the model – layer *4*. It leads to a slightly steeper *T(x)* in layer *1*, because the latter exchanges heat with a slightly colder layer *2*, which is in turn colder because it is exchanging heat with a colder layer *3*. Notice that saturation of layer-*1* temperature to an approximately linear profile needs at least 3 layers in the analysis.

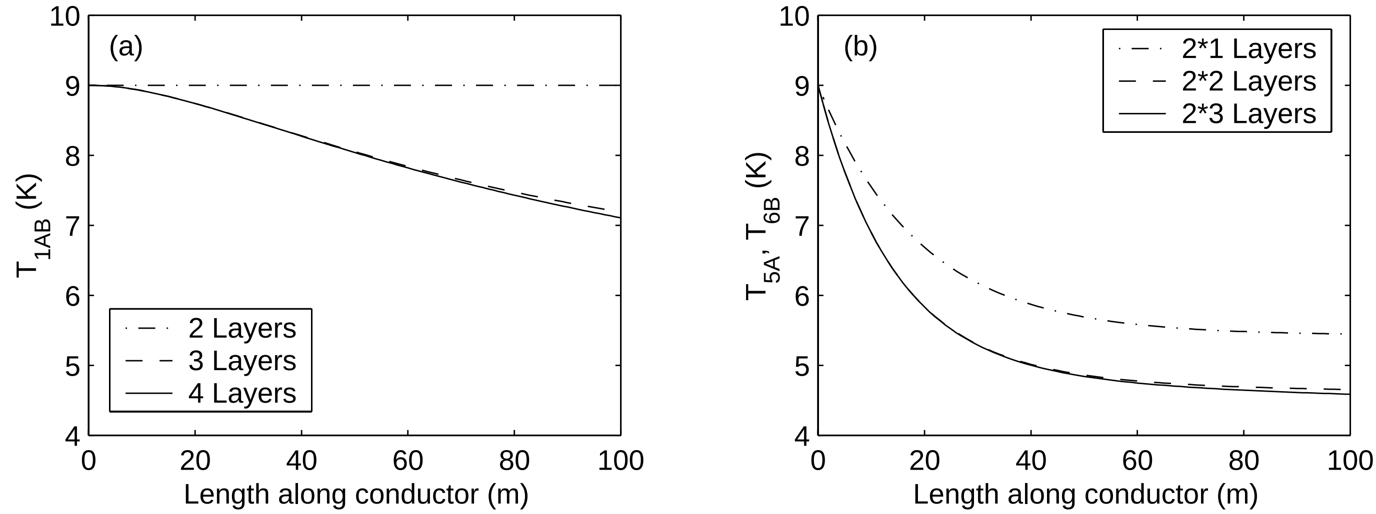

Figure 2 Computed *T(x)* along layer-*1* conductors (a) and along conductors *5A*, *6B* (b), for increasing number of thermally coupled layers.

3.2 Analysis of layer *5*

For the sake of simplicity, the conductors in layers *4-8* are assumed to have the same length $L_{4\text{-}8}$ = 115 m, and square conductor size $d_{4\text{-}8}$ = 0.046 m. Consider now Fig.2b. The situation is here very different from that of layer *1* because, as seen above, only conductors *5A* and *6B* are externally heated. If only layers *5* and *6* are included in the analysis, most of the temperature drop in the most critical conductor *5A* appears near the inlet because of heat exchange with *5B* and *6A*. This cooling is indeed much stronger than for layer *1*, where all conductors in the first two adjacent layers were externally heated. When also the first two adjacent layers (*4* and *7*) are included, a slightly steeper *T(x)* obtains in *5A*, for similar reasons as discussed above. This profile is already at saturation, i.e., accounting also for heat exchange with layers *3* and *8* does not lead to a significant change of *T(x)* in *5A*. Notice finally that, as opposed to *1A*, the T_{cs} measurement in *5A* cannot rely on the a-priori assumption of a linear *T(x)*.

3.3 Calibration of the model

Many uncertainties affect both (1) and (2). A calibration of the model could be performed using preliminary test results obtained by powering up the heaters with zero current in the coil. In other words, the solution of (1) at x = *L* can be equated to the measured T_{out} in each conductor (*not used to solve (1)!*), leading to a non-linear system with the $(hP)_{ij}$ as unknowns. The optimal values of $(hP)_{ij}$, leading to the minimization of the residual $\|T(x=L) - T_{out}\|$, can be found numerically. Notice that this best fit could be based on a broad set of measurements with the same mass flow rates but different heating power (if the latter, i.e., the Prandtl number, does not vary too much, the $(hP)_{ij}$ should also stay approximately unchanged).

In a separate step, the optimal $(hP)_{ij}$ could then be compared to the values used in sections 3.1, 3.2, leading to a critical evaluation of the heat transfer coefficient model given in (2).

3.4 Evaluation of T_{cs}

Since no experimental data are available at present for the model calibration, we compute the heat transfer coefficients using (2). In Figs.3a,b we compare the computed *T(x)* in *1A* and *5A*, respectively, obtained for T_{in}^{C} = 5.3 K, with $T_{cs}(x)$. The latter is obtained from the magnetic field computed at I = 46 kA on the inner lines of the layers [4], assuming longitudinal strain ε = –0.11%, B_{c20m} = 29.1 T, T_{c0m} = 16.9 K and $C_0 \sim 10^{10}$ $AT^{0.5}/m^2$. Thus, $T_{cs}(x)$ along *the axis* of conductor *1A* or *1B*, say, will lay between the two dotted lines in Fig.3a. *T(x)* in *1A* is computed using a suitable T_{in}^{H}, which leads to intersection/tangency with $T_{cs}(x)$, see Fig.3a. At this location the transition to the normal zone will be initiated. With the parameters used here (see above), a transition to the normal state seems to be possible somewhere before the location of the magnetic field maximum, but still near the middle of the conductor. Since *T(x)* in layer *1* is approximately linear, *the* T_{cs} of that conductor could be guessed approximately from linear interpolation between T_{in} and T_{out} measurements only, with an accuracy of ~ 0.1 K.

The magnetic field in layer *5* induces a very small variation (~ 0.5 K) of $T_{cs}(x)$ in *5A*. The strong heat exchange with non-heated conductors leads on the contrary to a significant drop of *T(x)* after conductor inlet,

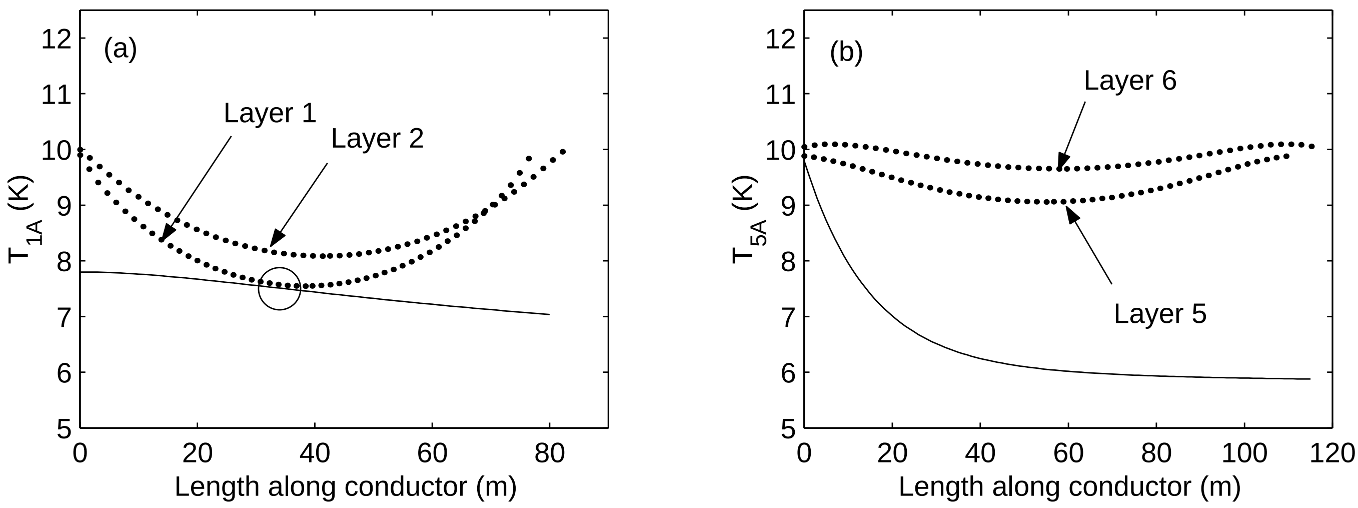

Figure 3 The tangency/intersection between the conductor *T(x)* (solid) and $T_{cs}(x)$ (dotted) in conductor *1A* (a) and *5A* (b), is used to determine *the* T_{cs} of the conductor. The magnetic field maps from which $T_{cs}(x)$ is obtained use the actual conductor lengths: ~77m for layer *1*, ~83m for layer *2*, ~110m for layer *5* and ~116m for layer *6*, and refer to the conductor inner line [4].

so that the only likely location to create a normal zone is near the He inlet. According to this qualitative result, the T_{in} measured when a normal zone is detected should be a good approximation for the T_{cs} of conductor 5A. (The use of higher T_{in}^{C}, for the same T_{in}^{H}, would lead in principle to a smaller temperature drop in conductor *5A*, but possibly also to quench initiation in inner layers.)

4 CONCLUSIONS AND RECOMMENDATIONS

A simplified model has been presented here to assess the procedure for T_{cs} measurement in the CSMC conductors *1A* and *5A*, using the available diagnostics. The computed results show that in the case of *1A* the approximation of a linear temperature profile of the conductor can be used to obtain T_{cs} within an accuracy of ~ 0.1 K, while in the case of *5A* one can rely on the inlet temperature signal as a good estimation of T_{cs}. However, many uncertainties are present in our model, and a calibration strategy was presented to assess the correct values of the heat transfer coefficients. For this, temperature data are needed and we recommend that they be collected for different external heating powers in a preliminary set of tests of the coil at zero current. The use of more sophisticated computational tools, such as the M&M code [5], accounting for the actual coil topology and for the 2-channel joint+conductor structure, is also recommended, both to confirm the qualitative results obtained here and for the quantitative interpretation of the tests.

5 ACKNOWLEDGMENTS

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