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3D thermal-hydraulic and electric modelling of quench propagation in HTS conductors for fusion

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Abstract—A fully three-dimensional multi-physics model to simulate quench propagation in HTS conductors for fusion applications is presented. It accounts for thermal, electric and fluid dynamics throughout the entire transient. It gives a deeper insight into the evolution of relevant quantities, e.g., the temperature in the bulky structure of the conductor, with respect to the typical 1D models. A preliminary validation against experimental results show satisfactory agreement.
Keywords—3D, thermal-hydraulic, electric, quench, HTS

INTRODUCTION

Quench propagation in high current conductors based on High Temperature Superconducting (HTS) material is an open issue due to the small normal zone propagation velocity. This makes the quench much more challenging to be detected than for conductors made of Low Temperature Superconducting (LTS) materials. For this reason, an extensive test campaign is ongoing within the EUROfusion Consortium in order to characterize experimentally different conductors design from the quench point of view. Also, this experimental campaign aims at building a database to calibrate and validate numerical models which can then be more reliably used for the simulation of quench in full conductors and/or on different designs.
Several conductors have already been tested [1] and more will be tested in 2024. A calibration and validation exercise has been successfully accomplished [2] modelling the quench propagation with a 1D code [3].
This modelling approach is based on lumping the cross-section of the solids and of the fluids in each axial nodes. This implies assigning a single value of temperature for the solids and of speed, velocity and temperature for the fluids.
However, this approach has some limitations, i.e., a limited capability in discretizing the cross-section of the conductor. This becomes important in the case of bulky structure as those foreseen in different designs of HTS conductors, see for example Figure 1. In order to provide a more detailed description of the three-dimensional distribution of relevant quantities, a fully 3D multi-physics model is presented here.

Figure 1 CAD view of the non-twisted conductor tested in the quench experiment in SULTAN. The dark orange squares are the stack of REBCO tapes, the light orange round regions are the copper profiles in which the stacks are enclosed, the cyan region are the voids where helium flows and the grey conduit is the jacket which serves as helium containment and mechanical support to the cable.
3D MODEL
The 3D model accounts for an electric, a thermal and a fluid model, which are coupled together to follow the transient under analysis.
Electric model
The current density distribution in each cell of the domain is computed from Eq. (1) reported below.
$\int_A \frac{1}{\rho} (\nabla\phi) dA=0$ (1)
where ϕ is the electric scalar potential, ρ is the electric conductivity and A is the cell face of a generic cell of the discretized domain.
The electric conductivity in the superconductor is given, according to the power law, as
$\rho=\frac{E_C}{J_C(B,T)} \left(\frac{J}{J_C(B,T)}\right)^{n-1}$ (2)

where EC = 100 μV/m, J is the current density and JC is the critical current density at the given magnetic field and temperature. The magnetic field is the background field of SULTAN, which has a peak value of 10.9 T in the High Field Zone (HFZ), which is much larger than the self-field, which is therefore neglected. The temperature is computed by the thermal model. The volumetric heat source is computed by the electric model according to the Ohm's law as Q = J·E.

The electric conductivity in the normal conducting region is temperature dependent and, in case of copper, it accounts also for the magnetic field and RRR.

Thermal model

The thermal model solves the 3D transient heat conduction equation. This equation is coupled to the fluid temperature one (see next sub-section) as well as to the electric one, as the Joule heating becomes the heat source as soon as the quench is initiated.

All the thermophysical properties are temperature dependent and, in case of copper, the thermal conductivity depends also on the magnetic field and RRR.

The density and specific heat capacity of the stacks of tapes are homogenized according to the mass and heat capacity, respectively, based on the composition of the layer of the tapes and of the solder among them.

Fluid model

The fluid model solves the full set of Navier-Stokes equations, computing the velocity, pressure and temperature of the helium in the voids where it flows, see Figure 1. The presence of turbulence is accounted for using a k-ω model for its closure. In order to cope with the strong non-linearities of the helium thermophysical properties, a coupled approach has been chosen as solver of the set of equations.

RESULTS

In this section, a preliminary validation against experimental data is reported. After that, the main results are briefly reported and discussed.

Preliminary validation against experimental data

In Figure 2(a), the comparison between the local temperature in the strand, in the helium flow and in the jacket show that the computed model is able to correctly follow the temperature increase in different locations of the conductor. Except for a small anticipation (roughly 2 s), the computed and measured temperatures agree, meaning that the model can be trusted to analyze more in detail the evolution of the transient.

This is also confirmed by the comparison of a local voltage measurement in the quenching region, see Figure 2(b).

(a)

(b)

Figure 2 (a) Temperature evolution in the quenching region of the conductor. The measured and computed strand and jacket temperatures are compared. (b) Measured and computed voltage evolution in the quenching region.

Jacket temperature distribution

In Figure 3, the distribution of the temperature of the jacket is reported, showing a strong non-uniformity in the cross section. Also, in Figure 4, on the external side of the jacket, a variation of 30 K (when the peak temperature there is 90 K) is obtained. This set of results shows quantitatively the implication of having a point contact of the quenching strands with the jacket and the thick structure of the jacket itself. These two features lead to a non-uniform distribution in the azimuthal direction and the second implies a slow heat propagation in the steel cross section, leading eventually to a three-dimensional transient distribution.

This can impact the capability of reliably following the this transient in a quenching conductor with other, simpler model. Also, this much more detailed model can give insight on the behavior of alternative quench detection strategies, e.g., fiber optics, which are sensitive to the local temperature distribution.

Figure 3 Computed temperature distribution on the external surface of the jacket and on its cross-section in the quenching region.

Figure 4 Azimuthal temperature distribution on the external surface of the jacket. A third of the external circumference is reported, corresponding to the red double arrow shown in the inset.

CONCLUSIONS AND PERSPECTIVE

A 3D thermal-hydraulic and electric model for the simulation of quench propagation in conductors for fusion applications has been presented. A preliminary validation shows it gives reliable results and the analysis of the quench evolution shows a fully 3D temperature distribution in the conduit of the cable. These results can help giving feedback to the design of alternative quench detection and to thermo-mechanical analysis, which are being implemented to understand the degradation mechanisms due to quench, which was experimentally observed in several conductors.

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Topic

Coupled and uncoupled multiphysics problems

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