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Thermal-hydraulic and quench analysis of the DEMO toroidal field winding pack WP1

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HIGHLIGHTS

- The quench transient in DEMO TF WP1 conductor is modeled.
- The hot-spot temperature dependence on quench detection parameters is investigated.
- The hot-spot temperature dependence on quench initiation zone is presented.

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ABSTRACT

Three alternative designs of the toroidal field (TF) coil were proposed for the European DEMO being developed under the Eurofusion Consortium. The most ambitious TF coil winding pack in terms of technological deviation from the ITER TF coil design and consequent potential cost saving, the so-called WP1, is based on the react&wind technology of Nb_3Sn layer-wound flat multistage conductors. We present the thermal-hydraulic and quench propagation analyses for the WP1 proposed in 2015, in which the realistic magnetic field and nuclear heat load maps are taken into account. The aim of the analysis, performed using the Cryosoft software, is to assess the temperature margin at the end-of-burn conditions, as well as the hot-spot temperature that is expected in case of quench, and consequently to optimize the WP1 design from the thermal-hydraulic point of view.

1. Introduction

The European DEMO fusion tokamak is being designed as a machine that will follow ITER reactor. The aim of DEMO is to demonstrate feasibility of electricity production, which has two consequences – firstly, the size of the device will be significantly larger than that of ITER, secondly, an emphasis is put on the cost efficiency of the employed technologies.

One of the main DEMO components is the toroidal field (TF) coil system, consisting of 18 identical coils [1]. The TF winding pack (WP) and conductor is being designed in four parallel versions – one of them is based on the high temperature superconductors, the other three on more conventional low temperature superconductors (LTS), namely Nb_3Sn and NbTi. One of the three LTS concepts, called RW1 design, is based on the layer-winding and react&wind technology. The present analysis is based on the latest update of the RW1 design [2], extending the earlier thermal-hydraulic studies [3–6] based on the previous TF WP design. Recent thermal-hydraulic analyses of the other two LTS WP concepts are presented in [6–8].

2. Conductor design

The DEMO TF winding pack RW1 is a graded layer wound coil [2], where every layer is optimized, i.e. the amount of superconductor, copper, helium and steel varies from layer to layer depending on the magnetic field, nuclear heat load and mechanical electromagnetic load in a given layer. It is based on Nb_3Sn material only. From a hydraulic point of view, the layers form parallel branches of the WP cooling circuit. The scheme of the cooling circuit can be found in [9].

The react&wind Nb_3Sn conductor, designed for operating current of 63.3 kA, is presented in Fig. 1 and described in detail in [2].

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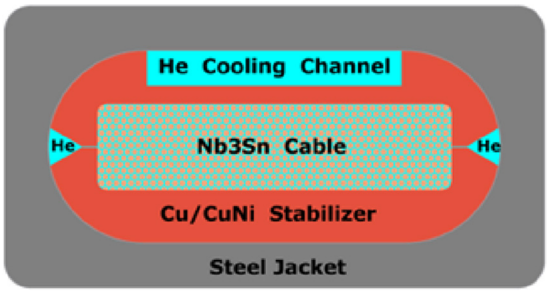

Fig. 1. React&wind conductor for the first layer of the DEMO TF coil.

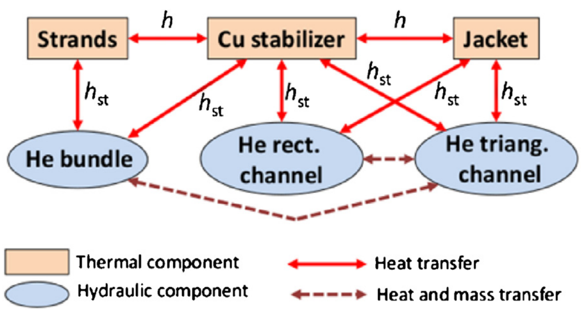

Fig. 2. Heat and mass exchange between the thermal and hydraulic components in the Thea model of RW1 conductor.

In the following we just summarize the main characteristics of the conductor relevant for the thermal-hydraulic analysis.

The conductor consists of a flat two-stage fully-transposed cable (19 strands in the first stage; 14 first-stage subcables in the bundle), a solid composite stabilizer made of 95% Cu and 5% CuNi (consisting of two adjacent profiles with a gap in between), two triangular and one rectangular helium cooling channels, and a steel conduit longitudinally welded around the conductor assembly. The boundary between Cu/CuNi stabilizer and the steel conduit is not tight, allowing helium exchange between the cable bundle and cooling channels. Helium flow is enforced by the pressure drop of 1 bar over the conductor length, with inlet pressure of 6 bar and outlet pressure of 5 bar. Helium inlet temperature is 4.5 K.

3. Thermo-hydraulic model

The thermo-hydraulic behavior of the conductor is investigated by the program Thea [10] from Cryosoft. The conductor is modeled as a 1-D system of several parallel components – three thermal components (strands, Cu/CuNi stabilizer and steel jacket) and three hydraulic components (He in the bundle, He in the triangular side cooling channels, and He in the upper rectangular channel). The friction correlation in the bundle region is based on the Darcy–Forchheimer equation [11], the friction correlations in the cooling channels in the turbulent regime are given by the Bhatti–Shah correlation [12]. Heat transfer h between the solid components is set to 500 W/(m^2 K) [13], where the contact surface between strands and copper stabilizer is assumed to be 1/5 of the overall boundary area. Heat transfer between helium and solid components, h_{st}, in turbulent flow is driven by the Dittus–Boelter correlation [13]. The details concerning the friction correlations and heat transfer coefficients in laminar regime, which may become relevant in part of the conductor during quench transient, are specified in [13]. Fig. 2 illustrates the heat-exchange links between the individual components.

We experienced a numerical instability in Thea when helium exchange was allowed between all three hydraulic channels. As a work-around solution, the helium exchange was enabled between

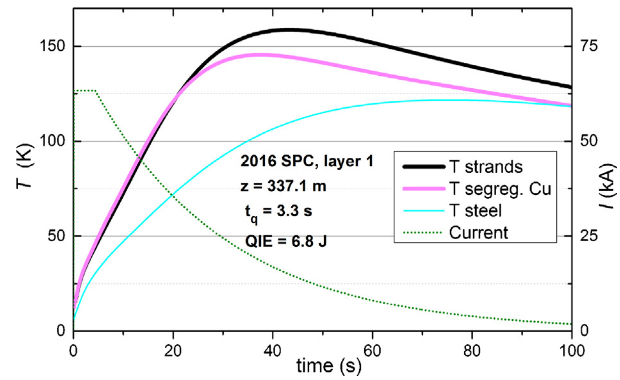

Fig. 3. Quench evolution in the conductor of layer 1 of the SPC RW1 coil simulated with Thea. Temperature is calculated at the hot spot location at z = 317.1 m.

bundle and triangular channel at elements no. 1, 3, 5, 7, . . ., and between upper channel and triangular channels at elements no. 2, 4, 6, 8, . . . This way the numerical problem was resolved, while helium exchange between all components was allowed. The effective opening between the bundle and the triangular channel as well as between the triangular and rectangular channels was 0.25 mm.

4. Quench calculations

The quench simulations were done on individual conductor layers, not taking into account heat transfer from layer to layer and from turn to turn. No heat transfer between the winding pack and its surrounding steel casing was considered. Magnetic field distribution (in fact effective magnetic field defined in [14]) along each conductor length was calculated using program M'C from Cryosoft. The contribution of magnetic field induced by plasma current, CS and PF coils at the end of burn conditions was taken into account.

First of all, a steady-state situation is modeled, in which nuclear heat load (e.g. 36.1 W in layer 1) is deposited for 3 h along the layer, and ohmic heating at the joint (2 W per layer) is generated at the initial 0.5 m of the conductor [15]. Mass flow rate, outlet temperature and some other variables for each layer are presented in Table 1. Temperature margin in all layers is at least 1.5 K. The steady-state is subsequently used as the initial state for the quench calculations. Helium flow is dominated by flow in the rectangular cooling channel, e.g. in the first layer the total of 18.3 g/s is sum of 17.2 g/s in the rectangular channel, 0.9 g/s in the triangular channels and 0.2 g/s in the bundle.

The quench is initiated by heating a 10 cm long initiation zone located somewhere near the conductor center, to avoid any edge-effects that might occur near the conductor ends, at the location of local maximum of the temperature margin. The quench initiated in the region of highest temperature margin is going to propagate slowest, and is therefore expected to lead to the highest hot-spot temperature, and becomes the worst-case (though the least likely) quench scenario.

The spatial adaptive mesh was used in Thea. The adaptive meshing is triggered wherever the temperature exceeds 6 K, with the minimum mesh size of 1 cm. Regardless of the temperature, a fine mesh of 5 cm long elements is set right from the beginning of the simulation in the region 5 m before and 5 m after the quench initiation zone. In the rest of the conductor (∼840 m in case of layer 1), the initial element size is set to 1 m.

The quench evolution in the layer 1, where effective magnetic field of up to 12.3 T [2] is the highest one, is presented in Figs. 3 and 4.

The quench initiation energy (QIE) was set two times higher than the minimum quench energy (MQE), and was deposited at

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