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Quasi-3D Numerical Simulation of TF Coil Thermal-Hydraulic Parameters During the Fast Energy Discharge

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Results of ITER TF coil thermohydraulic simulations during the fast energy discharge are presented. The simulations were performed for the reference discharge scenario and allowed preliminary assessment of basic dimensions for relief valves and quench lines.

Key words and phrases: ITER, TF coil, thermohydraulic simulations, full-scale quasi-3D calculation model, fast energy discharge, quench lines.

1. Introduction

Results of thermohydraulic simulations of a toroidal field (TF) coil of the International Thermonuclear Experimental Reactor (ITER) [1] during fast energy discharge are presented. The simulations were performed for the reference discharge scenario and allowed preliminary assessment of basic dimensions for relief valves and quench lines. The aim was to clarify safety of discharge process for the TF magnet system with a proposed set of relief valves and quench lines for helium extraction. The study was performed with the use of a full-scale quasi-3D calculation model of a TF coil that had been intensively applied to simulation of the ITER TF magnet operation [2].

The model is formed by basic mathematical models for typical magnet components such as a superconductor, circulating pump, cooling channels, collectors, heat exchangers, helium tanks, valves etc. Each component is described by an individual set of differential equations. The basic models are linked into a generalized model by thermal and hydraulic coupling. For simulation of the fast energy discharge, the full-scale TF model was combined with a simplified hydraulic model of the quench lines as shown in Fig. 1. The simulations were performed using the original code VINCENTA intended for prediction of transient thermohydraulic behaviour of superconducting magnets cooled by forced flow of single- or two-phase helium. The TF coil behaviour was modelled in terms of realistic geometry, non-linear material properties, relief valve operation, and time and space variations of heat loads.

2. TF Coil Calculation Model

The TF magnet system in ITER is configured as 18 identical D-shaped coils with steel cases. A coil winding consists of cable-in-conduit conductors in which forced supercritical helium is supplied to cool. A winding pack and a case have separate cooling loops. During a fast energy discharge, it is expected that a TF coil will be heated up to 50 to 60K, and the helium inventory in the coil and case will be expelled into an external helium tank (quench tank).

The calculation model involves thermal and hydraulic description of the TF coil components:

- 7 pancakes of the TF coil winding pack (for a half coil);
- 32 2D cross sections for modelling thermal diffusion in the TF case and radial plates;

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– 50 cooling channels of TF case grouped into two parallel branches;
– return/supply cryolines for the TF WP and TF case cooling circuits;
– individual description of time and space variations of heat losses associated with eddy currents in the TF case elements;
– local models of two centrifugal pumps for forced flow of He in the TF WP and TF case cooling circuits;
– local model of a saturated helium bath with immersed heat exchanger.

A hydraulic layout of the TF coil and the quench loop used in the simulation is shown in Fig. 1.

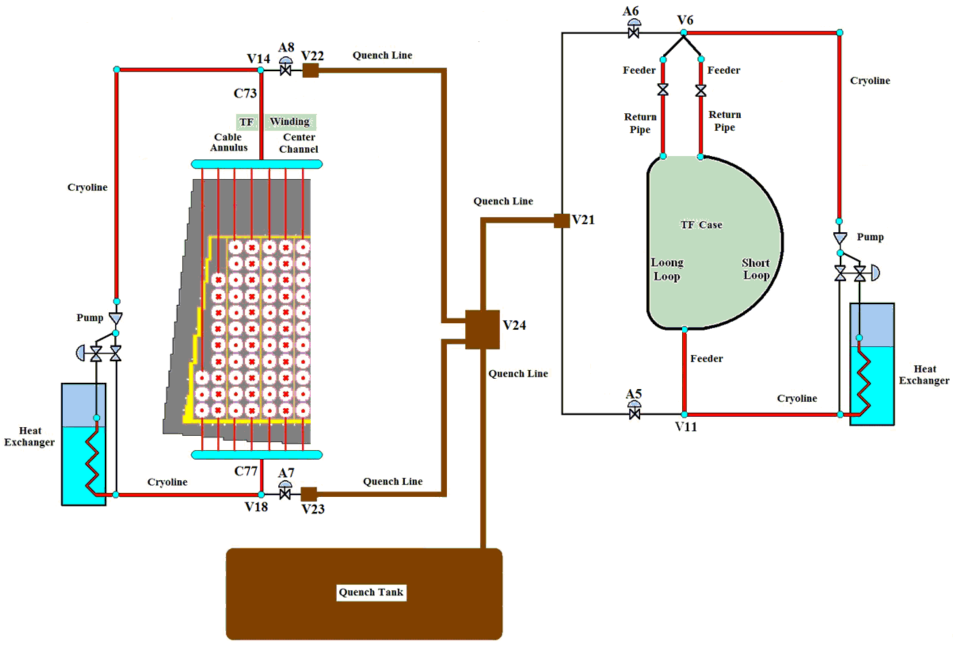


Figure 1. **TFC hydraulic layout used for the normal operation and fast energy discharge analysis**

3. Components of the Quench Loop

The outer quench loop includes the following components:

– 720 m^3 cold quench tank having an initial temperature of the wall and inside helium of 80 K. The initial He pressure inside the quench tank is 0.1 MPa;
– a system of initially warm (300 K) helium quench lines that consists of one TF case tube (C81) of the total length of 40 m, 2 identical TF winding tubes (C82 and C83), each of 100 m in length and one common quench line (C84) of 60 m in length. Inner diameters of the TF case tube, TF winding tubes and the common quench line are 100 mm, 150 mm and 300 mm respectively. The initial He pressure inside the He lines is 0.1 MPa;
– 4 He relief valves (A5&A6 and A7&A8) installed at inlet and outlet of the 18 TF cases/winding packs. These valves start opening when the pressure upstream overcomes the threshold pressure of 1.6 MPa [Fig. 2]. The prestart thermal-hydraulic state of a simulated TF coil was assumed to occur at the end of steady state 400 s plasma pulse. The simulation started from the plasma disruption followed by the energy fast discharge after 2 s. In the simulation, it was assumed that both pumps were switched off.

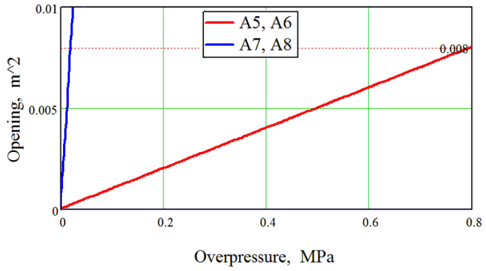


Figure 2. **Opening law for the TF cases / winding relief valves**

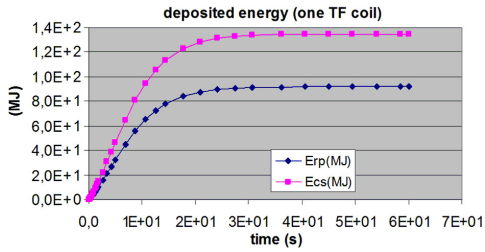


Figure 3. **Energy release in the TF case and winding versus time during the fast discharge**

4. Heat Load Scenario

The eddy current heat losses inside the TF structure due to eddy currents have a transient nature. Corresponding heat deposition onto 96 different TF cases parts and radial plates was assessed by the IO team [Fig. 3]. The total eddy current losses for the TF winding and TF case are 2.4 GJ and 1.65 GJ respectively.

5. Results of Simulation

The computations have given prediction for thermal and hydraulic responses of the TF magnet system and its cooling loops during 200 s of the fast energy discharge. Figures 4–11 present simulated evolution of representative parameters for different components of the TF magnet.

A pressure evolution upstream the case circuit relief valves A6 (volume V6 in Fig. 1), A5 (volume V11) and downstream the both valves (volume V21) is shown in Fig. 4. As seen, the pressure upstream the valves reaches the threshold pressure of 1.6 MPa at 4.0 s.

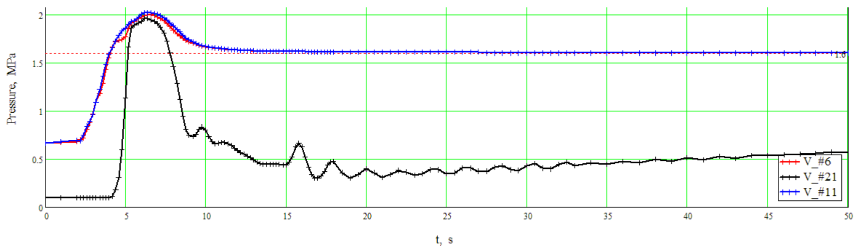


Figure 4. **Pressure evolution upstream valve A6, upstream valve A5 and downstream both valves**

Fig. 5 illustrates a pressure evolution upstream the winding circuit valves A8 (volume V14) and A7 (volume V18), downstream the valves A8 (volume V22) and A7 (volume V23), and in volume V24. The pressure upstream the valves reaches the threshold pressure of 1.6 MPa at 7.2 s.

Variations of the helium mass flow rate through valves A5, A6 are presented in Fig. 6. Totally, 179 kg of helium have been expelled through A5 and 144 kg of helium through A6.

Variations of the helium flow rate through valves A7 and A8 are shown in Fig. 7. Totally, 2121 kg of helium have been expelled through A7 and 1959 kg of helium through A8.

Due to compressibility of helium and complex feedback in the quench circuit, the pressure and flow rate oscillations upstream and downstream of valves are observed

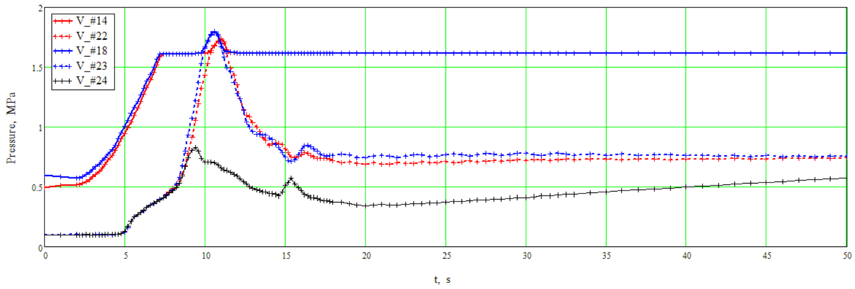


Figure 5. **Pressure evolution upstream valve A8, upstream valve A7, downstream valve A8, downstream valve A7 and in volume V24**

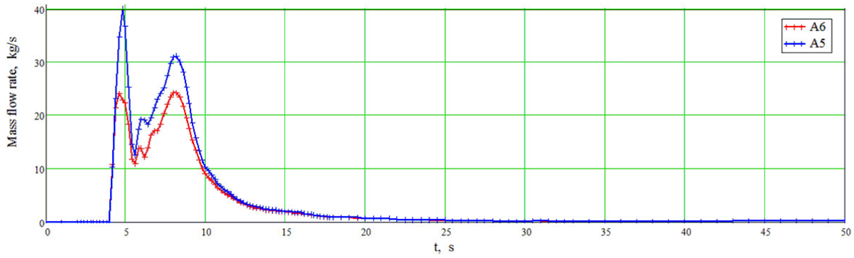


Figure 6. **Evolution of helium mass flow rate through A5 & A6 valves during TF coil fast energy discharge. 179 kg of helium have been exhausted through valve A5 and 144 kg of helium through valve A64**

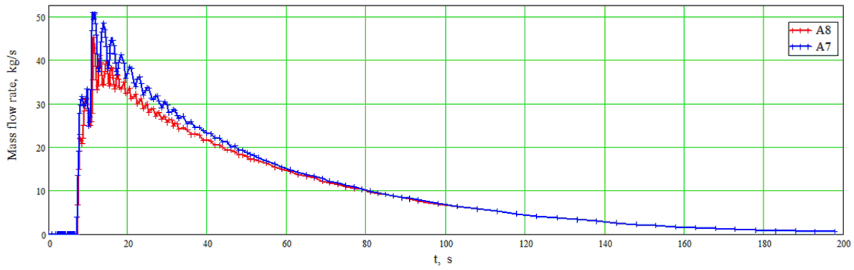


Figure 7. **Evolution of helium mass flow rate through A7 & A8 valves during TF coil fast energy discharge. 2121 kg of helium have been exhausted through valve A7 and 1959 kg of helium through valve A8**

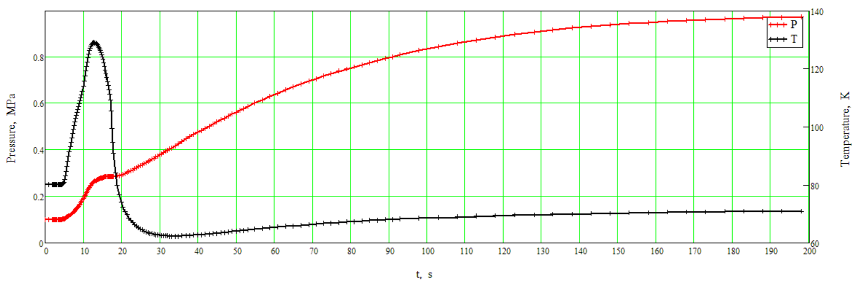


Figure 8. **Evolution of pressure and temperature inside the quench tank**

during the period when the helium density gradients along the quench lines are high. Evolutions of the pressure and temperature inside the quench tank are presented in Fig. 8.

The following evaluation has been obtained for helium mass reduction in the TF magnet system at the fast energy discharge:

– total 3918 kg for all windings;
– total 166 kg in the cooling channels of all cases;
– total 153 kg in the TF cases interface loop (feeders, return/supply cryolines, heat exchanger).

Totally, helium in conductors has absorbed and evacuated 790 MJ of heat releases. This amount is a half of the heat released inside the TF radial plates.

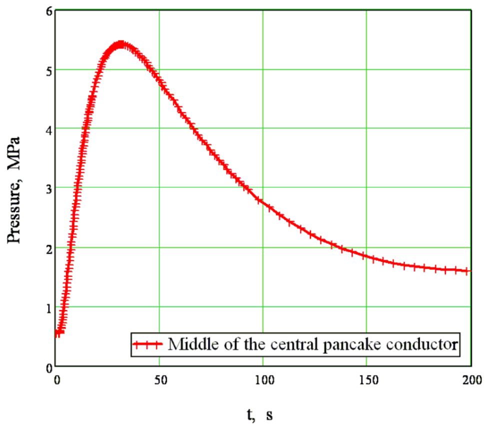


Figure 9. **Helium pressure evolution of in the middle of the central pancake conductor**

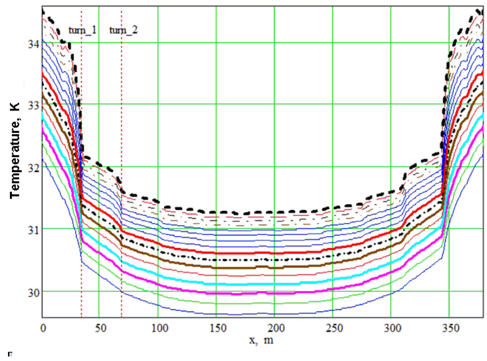
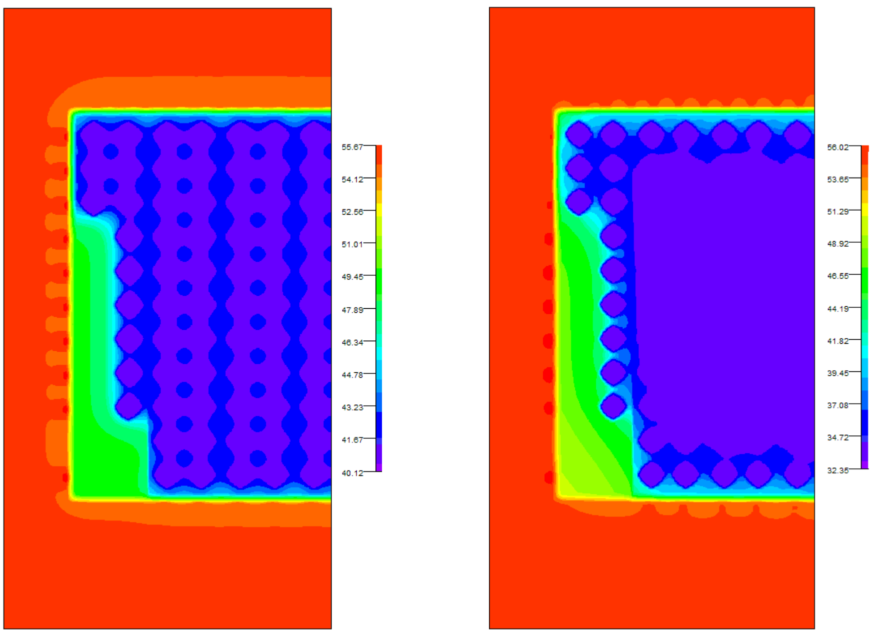


Figure 10. **Temperature evolution at interval from 123 s to 198 s along the central pancake conductor**



a) b)

Figure 11. **Temperature maps for a typical cross section of the TF coil at 50 s (a) and 200 s (b)**

A pressure evolution of helium in the middle of the TF conductor is shown in Fig. 9. Temperature evolution along the TF conductor at the interval from 123 s to

198 s is given in Fig. 10. As seen, the temperature of cables continue to rise but much slowly than in the beginning of process. At 200 s, the temperature of cables is close to the temperature of the radial plates which is growing slowly due to heat coming from the TF cases [see Fig. 11]. This distribution reflects the fact that the main transients in the winding are practically finished.

Temperature maps for typical cross section of the TF coil at 50 s and 200 s are presented in Fig. 11.

6. Conclusion

The thermohydraulic simulations of the TF fast discharge have revealed that

1. It takes 15 s to extract helium from the TF case and about 200 s to exhaust the winding (Fig. 6–7).
2. Due to small diameter of the quench tubes and fast warming of the helium inside, the maximum pressure in the TF case exceeds 2.0 MPa. The same reasons cause a 1.8 MPa pressure spike in the TF winding quench circuit at 10 s of the fast discharge (Fig. 4–5).
3. He pressure and temperature inside the cold quench tank of 720 m^3 reach, respectively, 1 MPa and 42 K at 200 s and keep rising due to equalizing of temperatures between the helium and the tank wall (Fig. 8).
4. Parameters of the relief valves and diameters of the quench lines should be specified more accurately after optimization of the quench circuit schematic.

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Квази-трёхмерное численное моделирование термогидравлических процессов при быстром выводе энергии из обмотки тороидального поля

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Представлены результаты численного моделирования термогидравлических процессов при быстром выводе энергии из обмотки тороидального поля. Моделирование выполнялось для базового сценария вывода энергии и позволило дать предварительную оценку размеров предохранительных клапанов и криогенных труб.

Ключевые слова: ИТЭР, обмотка тороидального поля, моделирование, полномасштабная квази-трёхмерная вычислительная модель, быстрый вывод энергии, термогидравлические процессы, криогенные трубы.