On a full 3D thermal structural and hydraulic FE model of the JT-60SA toroidal field coils

V. Tomarchio, M. Wanner

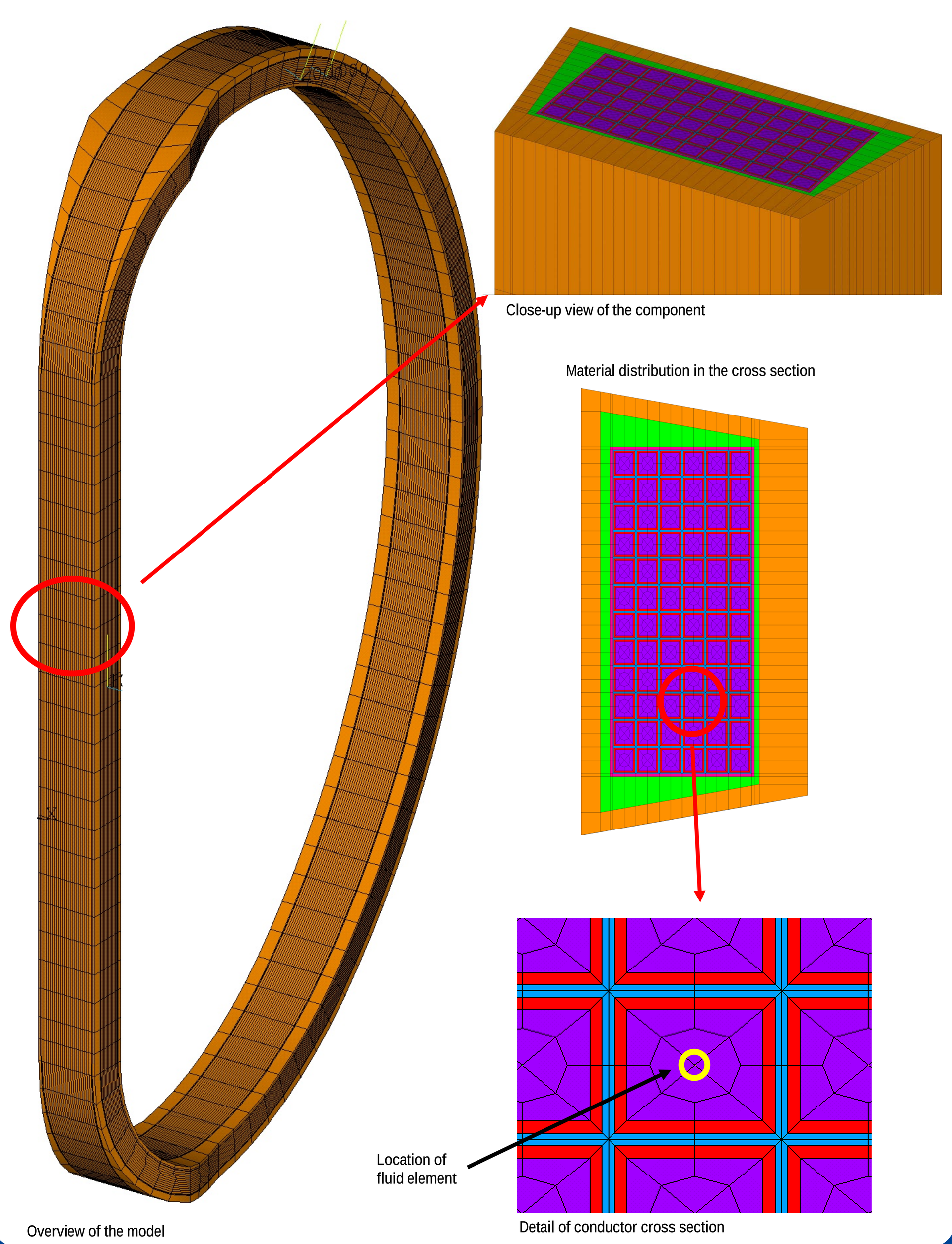
Fusion For Energy – Broader Fusion Development Department – Boltzmannstr. 2 – D-85748 Garching bei München - GERMANY

Introduction

- The JT-60SA Toroidal Field Coils (TFC) are currently being manufactured in Europe, and their assembly is progressing at full speed in QST, Naka. As part of their final acceptance, the coils are tested at 4 K and nominal current in a dedicated facility of CEA in Saclay.
- To help define the cool down strategy for the testing of the TFCs, and also to anticipate their behaviour during the cooling down of the JT-60SA tokamak, a fully 3D finite element model of a TFC has been created, which includes finite elements with thermal, mechanical and hydraulic formulations, to simulate in real time the interaction between the helium coolant flow and the structures.
- The model has been extensively used for predicting the behaviour of the TFC during cool down and warm up, and the results have been benchmarked against the experimental evidence collected during the cold tests carried out in Europe. Several kind of analyses were carried out, from simple cool down simulations, to more sophisticated simulations of fast transient events, like the dynamic quench test which all TFCs have undergone.
- The model is built using the commercial ANSYS Finite Element code and is readily up-scalable to any size of similar magnets.

Description of the model

- 3D, fully parametric ANSYS APDL model.
- SOLID70 (thermal) + FLUID116 (hydraulic) elements.
- All material properties defined between 4 and 300 K.
- Helium material properties based on HePak© and integrated in ANSYS through tables.
- Thermal and hydraulic solution are directly coupled, mechanical and electromagnetic solutions can be obtained on the same mesh.
- WP modelled in detail: 72 turns, 6 double pancakes hydraulically in parallel, electrically in series.
- Transverse conduction is directly solved by the thermal solver.
- Convective heat exchange based on experimental characterization of real conductors.

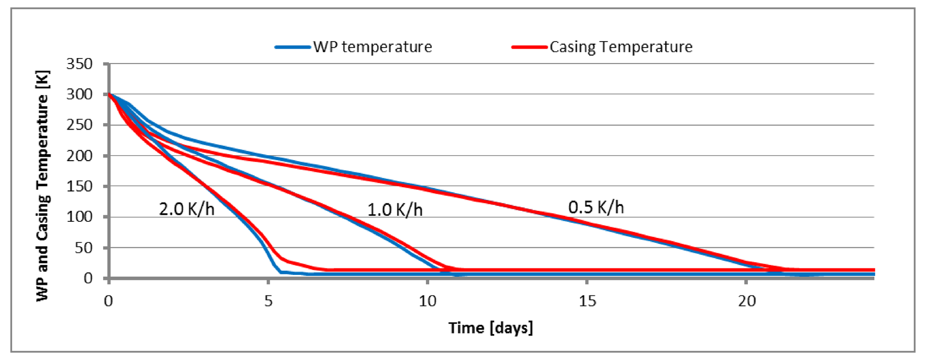


Model set-up and Benchmarks

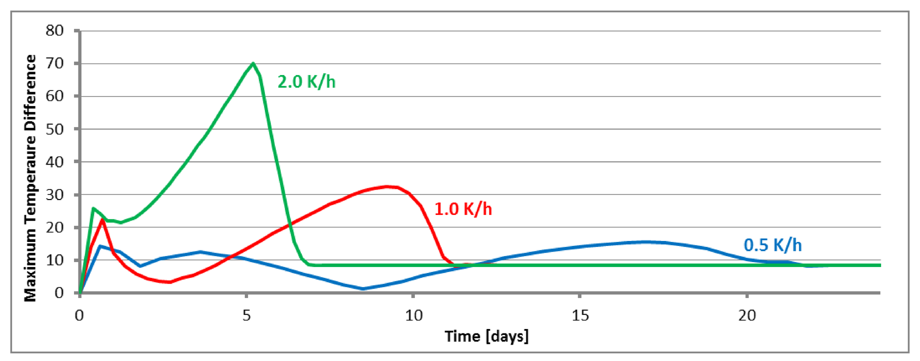
- Several loads and boundary conditions can be applied to the model:
  - Helium flow, inlet temperature, inlet and outlet pressure
  - External surface radiation, internal heat generation, localized heat input (e.g. from supports)
  - External convection (e.g. due to a loss of coolant)
- Several benchmarks have been run to validate the model:
  - Cooling down characterization
  - Pressure drop characterization
  - Delta T characterization
  - Dynamic response (temperature step, quench ramp)

Cooling down characterization

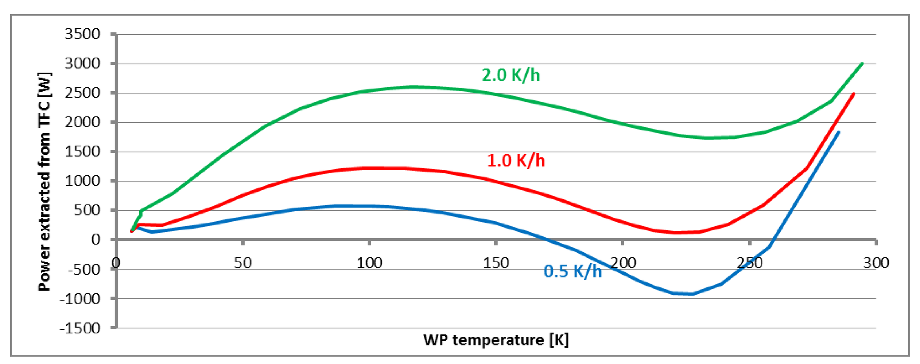
- Used to predict the time for complete cool down, without exceeding the critical temperature gradient on the coil structures.



WP and casing temperatures during three simulated cooldowns at constant cooling rate.



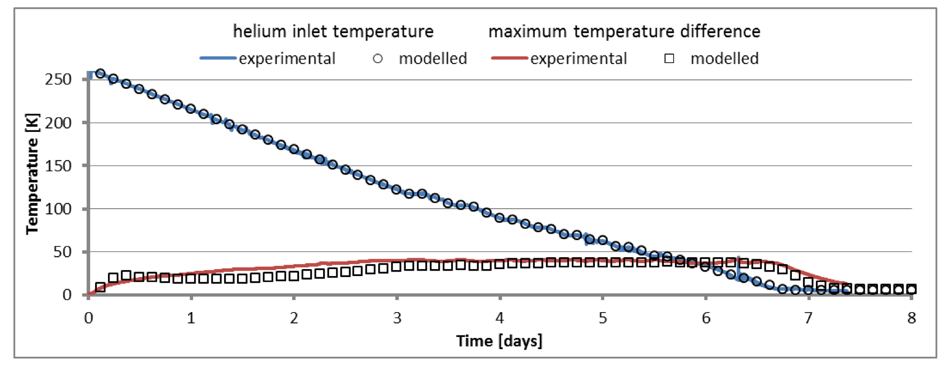
Maximum temperature gradient across the coil casing during three simulated cooldowns at constant cooling rate.



Cooling power required during the three simulated cooldowns as a function of WP temperature

Model set-up and Benchmarks

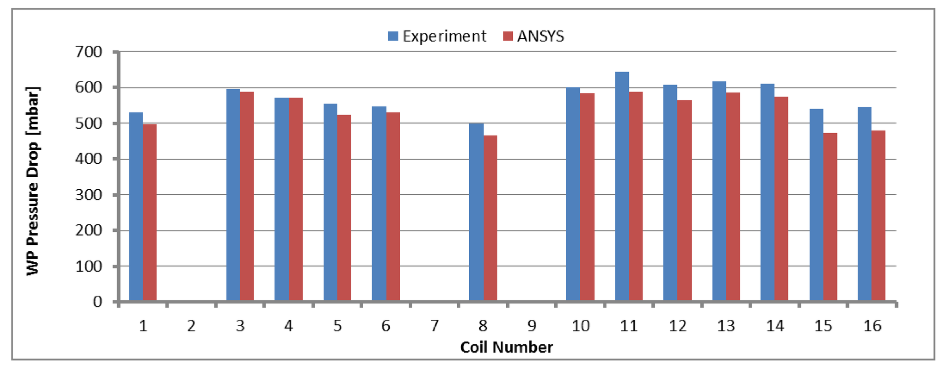
- The model predicts well the maximum thermal gradient across the casing and can be used to define variable cooling rates to optimize cool down time.



A variable cool down rate transient simulated with the model and compared to the CTF data

Pressure drop characterization

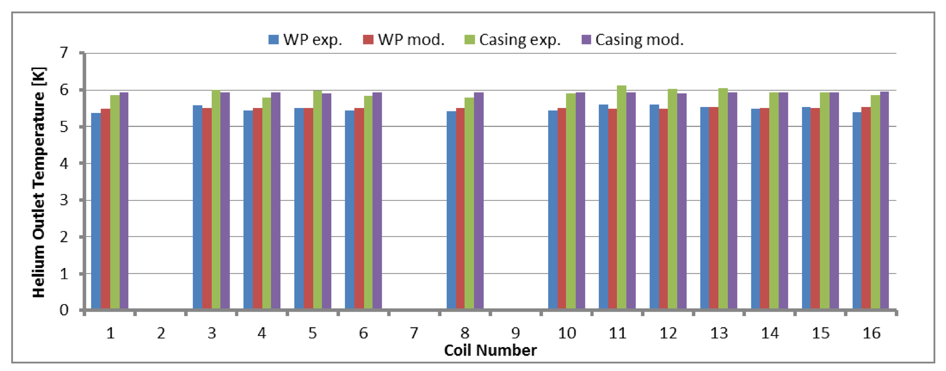
- The pressure drop of the TFCs obtained by the model has been compared with the experimental evidence obtained during cold testing.
- Agreement is very good (deviation < 10%) small differences are due to the external piping resistance which is not modelled.



Validation of pressure drops at cryogenic conditions and full current.

Delta T characterization

- The helium temperature difference between inlet and outlet of the TFC at cryogenic conditions and at full current has been calculated and compared with the cold test results.
- Agreement is very good (deviation <5%)

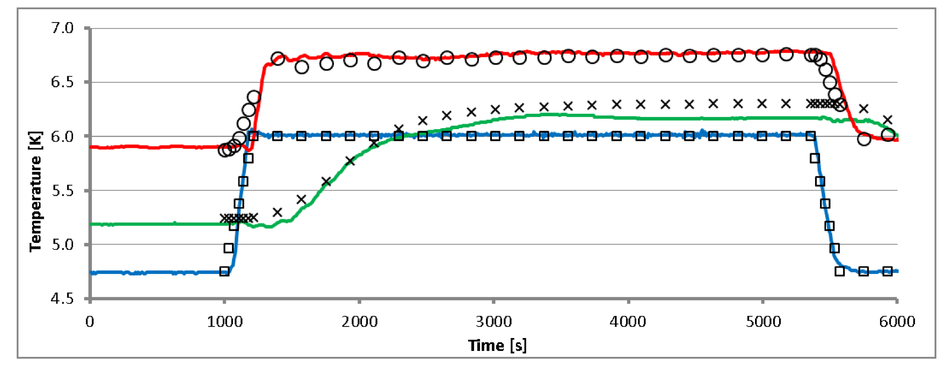


Validation of helium temperatures at cryogenic conditions and full current.

Dynamic response

Step response

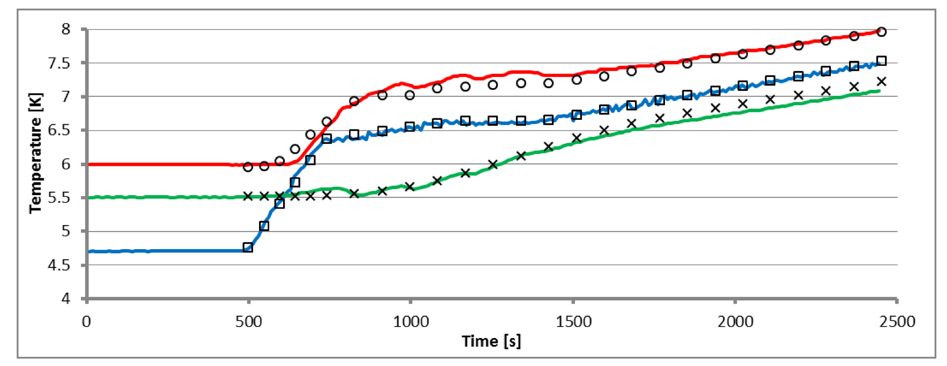
- A temperature step was imposed at the helium inlet of a TFC in cold stand-by conditions. The temperature evolution at the outlet was recorded by the CTF.
- The response was much faster with respect to the transit time of the helium in the pancakes due to transversal conduction in the WP and casing.
- The model well reproduces this phenomenon, both in absolute values and in dynamic response, capturing the smoothing out of the input temperature step in the corresponding output step, given by the cross conduction in the conductor layers and the external heat input.



Simulation of a temperature step response. Inlet (blue), WP outlet exp. (green), casing outlet exp. (red), Inlet modelled (squares), WP outlet modelled (crosses), casing outlet modelled (circles)

Temperature ramp

- Each coil undergoes a relatively fast transient during execution of the quench test,
- A step inlet helium temperature increase followed by a slow increasing ramp has been simulated using the model,
- The model captures accurately the steady state values before the temperature step, and also the dynamic response of the step and the following ramp.
- This further demonstrates how transverse heat transport is fundamental in properly defining such computational models.



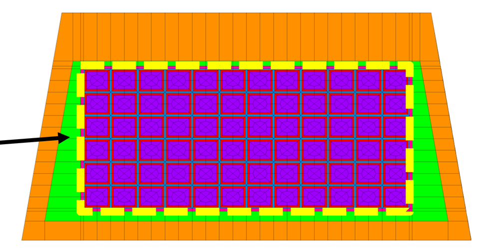
Simulation of the temperature ramp prior to quench test. Inlet (blue), WP outlet exp. (green), casing outlet exp. (red), Inlet modelled (squares), WP outlet modelled (crosses), casing outlet modelled (circles)

Issues and challenges

Thermal contact between WP and casing

- The heat transfer between the internal surface of the casing and the external surface of the WP is dominated by conduction, and this is as good as the contact pressure between the two components, which is not constant in time during the cool down and operation of the coil.
- The model has an adjustable thermal boundary between WP and casing, whose thermal conductivity can be adjusted case by case. The experience accumulated with the cold testing of the TF coils has allowed the fine tuning of this boundary.

Thermal boundary to be adjusted



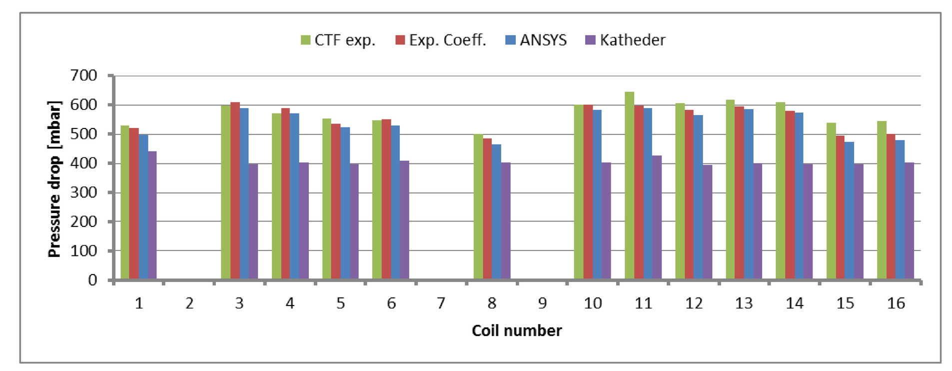
Hydraulic friction factor

- The pressure drop in the coil is dominated by the pressure drop in the WP (i.e. in Cable in Conduit Conductors). Existing correlations cannot be applied as-is to JT-60SA.
- Katheder formula, for example, would underestimate the pressure of about 20% - 50% compared to the experimental one.

$$f_{Katheder} = \left(\frac{1}{\upsilon^{0.72}}\right)\left(0.051 + \frac{19.5}{Re^{0.88}}\right)$$

- For JT-60SA each conductor has been characterized at relevant Reynolds number, and the obtained friction factor have been used in the model to calculate the pressure drop and agreement is well within 10%.

$$f = \alpha + \beta R_e^{\gamma}$$



Comparison of pressure drops in energized coils as measured by the CTF and as calculated analytically (red), by the model (blue) and using Katheder formula (purple). The model accurately reproduces the measured values.

Conclusions

- The presented model has played an important role in the definition of the TFC testing strategy, and has provided interesting answers to questions related to coil operation, cooling system fault management and overall cryoplant operating balance.
- The model is scalable and adaptable to different coil designs, either pancake or layer based, and can be used both as a design or validation tool.
- The formulation adopted is suitable for representing relatively fast transients with time scales of minutes or more. It is not suitable though for really fast transients, like quench simulation, or transients where flow compressibility is the driving mechanism.
- The model can be further extended in its multi-physics approach and can be easily adapted to accept the future challenges of ITER and DEMO.