Development of a 2D simplified tool for the analysis of the cooling of the ITER TF winding pack

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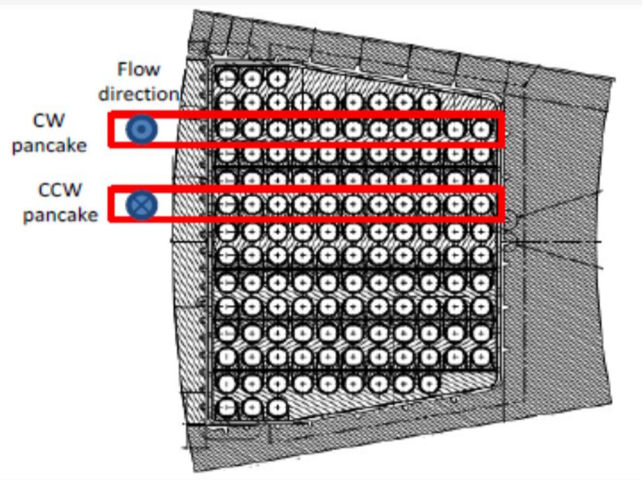
Thu-Af-Po4.02-02 [16]

FUSION FOR ENERGY

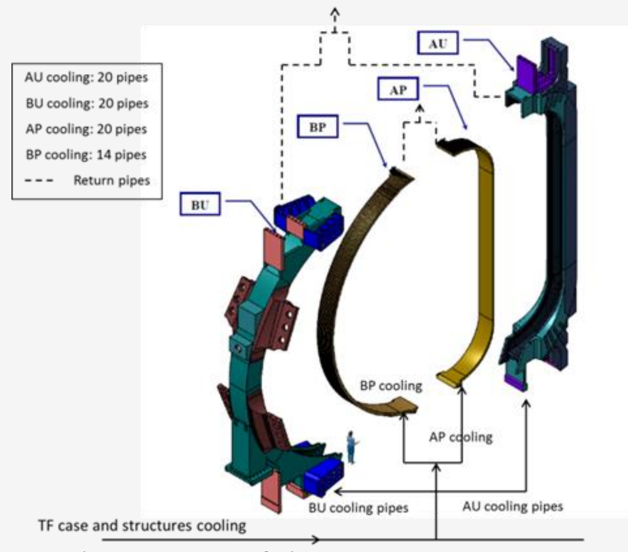
The cooling of the ITER Toroidal Field (TF) coils winding pack is guaranteed by the circulation of supercritical Helium (He) in 134 Nb_3Sn Cable in Conduit Conductor (CICCs) and in 74 channels devoted to the cooling of the Stainless Steel (SS) Case supporting the winding pack. A simplified tool aimed at computing the temperature distribution and the He temperature in the cooling channels of the TF winding pack has been developed. The advantage of this tool, which is based on 2D FE thermal analyses and has been entirely developed inside ANSYS with the APDL language, is that is able to provide the temperature reached by He during plasma operation. The heat load that has been considered is the volumetric nuclear heating computed with the MNCP code in 32 poloidal segments in which TF coil has been divided. For each segment, a 2D FE model has been built and a thermal analysis carried out by applying the corresponding heat load. Steady state analyses have been done considering the baseline pancake wound configuration, and two ideal layer wound configurations. In a second step, a preliminary transient analysis of the pancake wound configuration has been also carried out, considering the actual ramp up and ramp down of the nuclear heating.

COOLING LAYOUT OF THE ITER TF COIL

- The cooling circuit of the TF WP is made by the circulation of Helium in the CICCs. Each DP has the helium feed and return connection at the lower terminal junction, in which helium is driven to flow into two opposite flow directions, clockwise and counterclockwise.
- The cooling circuit of the TF case is equipped with parallel cooling circuits that run in the poloidal direction grouped in parallel sets.

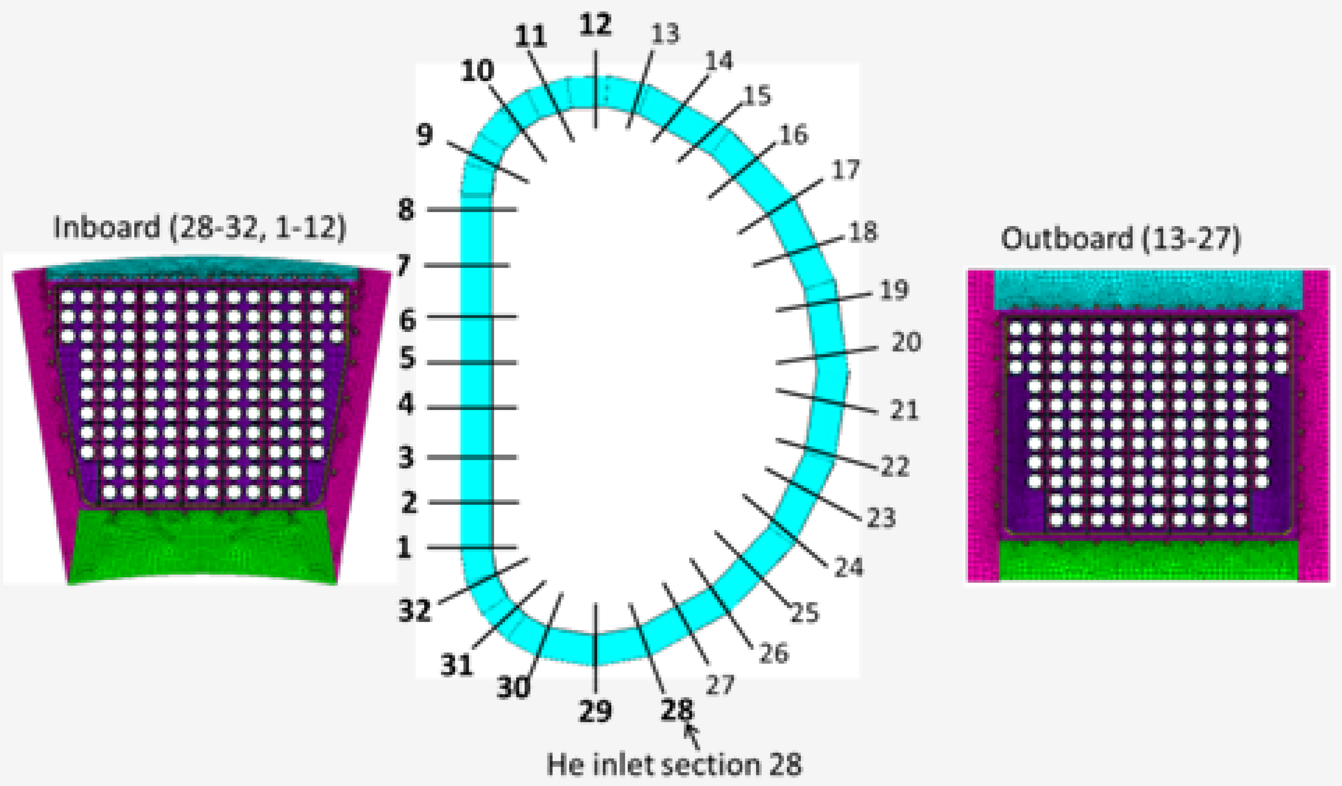


Cooling Layout of the TF WP



Cooling Layout of the TF case

FE MODELS

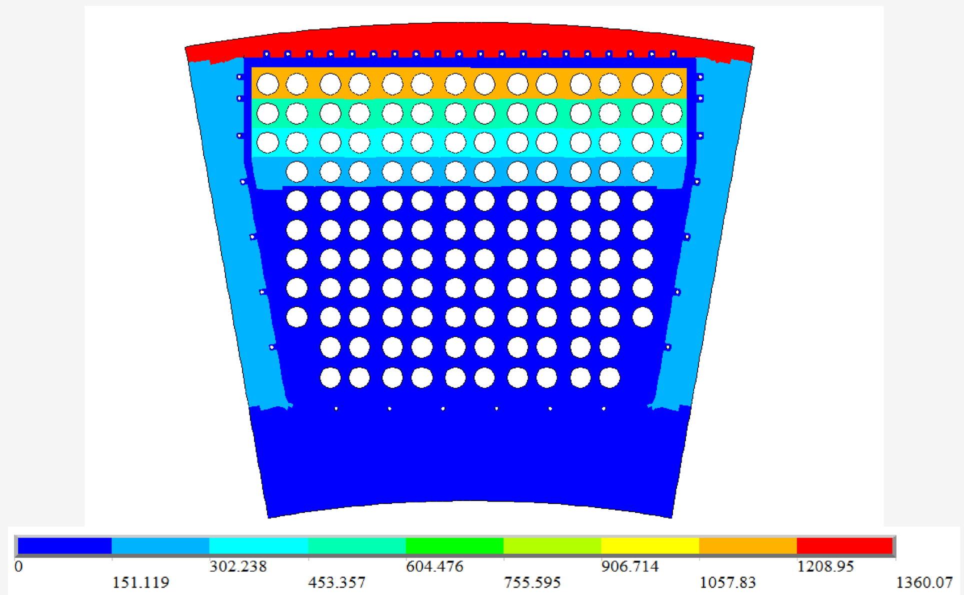


TF poloidal segments: inboard segments (in bold) and outboard segments

LOADS

- The "best estimate" of the nuclear heat load on the TF Coils is defined as 18.5 kW for the 18 TF Coils, while the more realistic "conservative estimate" is assessed to be equal to 21.57 kW.
- The analysis has been performed applying the "conservative estimate" plus uncertainties (around 21%) for a total heat load of around 26.10 kW.

TF Coil Regions	Best estimate	Conservative estimate
Inboard straight leg (1-7)	12.01 kW	11.01 kW
Inboard top (8-11)	1.58 kW	3.38 kW
Outboard top (12-16)	1.05 kW	2.19 kW
Outboard equatorial (17-22)	0.63 kW	2.04 kW
Outboard bottom (23-28)	2.65 kW	2.33 kW
Inboard bottom (29-32)	0.56 kW	0.62 kW
TOTAL	18.48 kW	21.57 kW



Volumetric Heat Load [W/m^3] on section #5

1D HELIUM COOLING CIRCUIT MODELS

- The flow repartition inside CICC is computed with the momentum equation assuming that the density is constant and that the pressure gradient in the bundle and in the central channel is the same along the fluid path
- The HTC between bundle and hole regions h_{HB} has been assessed considering the surface perforation parameter p of the spiral, $h_{CR,i}$ (i=B,H) are the heat transfer coefficient in the two regions computed with the Colburn-Reynolds analogy, e is the spiral thickness and λ_{SS} is the Stainless Steel thermal conductivity.
- Regarding the HTC between the bundle region and the jacket h_{JB}, it has been implemented the correlation derived by experimental results where $t_{He,layer}$ is the stagnant Helium layer thickness in the cable wraps and $\lambda_{He,layer}$ is the Helium thermal conductivity

	Hydraulic diameter	Mass flow rate
CICC bundle (B)	≈0.341 mm	3.002 g/s
CICC hole (H)	8 mm	4.898 g/s
Case cooling pipes	7.8 mm	2.700 g/s

$$f_H = 1.3 \times 0.3024\,\mathrm{Re}_H^{-0.0707}$$

$$f_B = (1/\varphi)^{0.742}\left(0.0231 + 19.5/\mathrm{Re}_B\right)^{0.7953}$$

$$h_{HB} = \frac{h_{CR,B} h_{CR,H}\, p}{h_{CR,B} + h_{CR,H}} + \frac{\lambda_{SS} h_{CR,B} h_{CR,H} (1-p)}{\lambda_{SS}(h_{CR,B} + h_{CR,H}) + e h_{CR,B} h_{CR,H}}$$

$$h_{JB} = \frac{1}{1/h_{CR,B} + t_{He,layer}/\lambda_{He,layer}}$$

$$f_{pipe} = (0.79 \ln \mathrm{Re} - 1.64)^{-2}$$

$$h_{pipe} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$$

STRATEGY

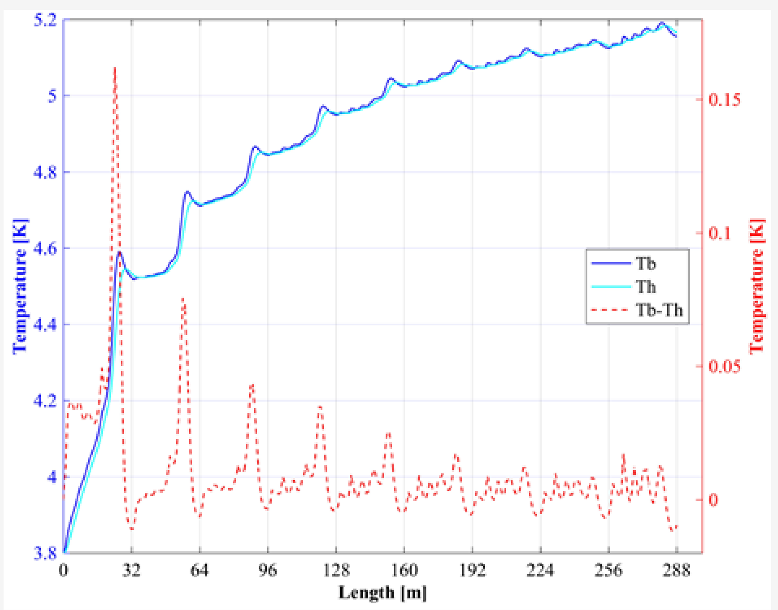
For the solution of the steady-state analyses, an appropriate iterative procedure has been set-up, summarized by the following steps:

- First run of 2D FE thermal analyses with initial values of Helium bulk temperature equal to 3.8 K in both WP and TF Case cooling circuits, applying to the 32 sections the corresponding nuclear heat load. For each 2D section, the power extracted from each CICC and each pipe is stored;
- Solution of the Helium cooling circuits by means of the 1D thermal-hydraulic models using the powers stores in step (1);
- Storing of new bulk temperatures computed in step (2) and evaluation of the new respective HTCs;
- Following run applying the same heat load and the new convective conditions computed in step (3). Newly, the power extracted from each CICC and each pipe is stored and loop restarts from step (2).

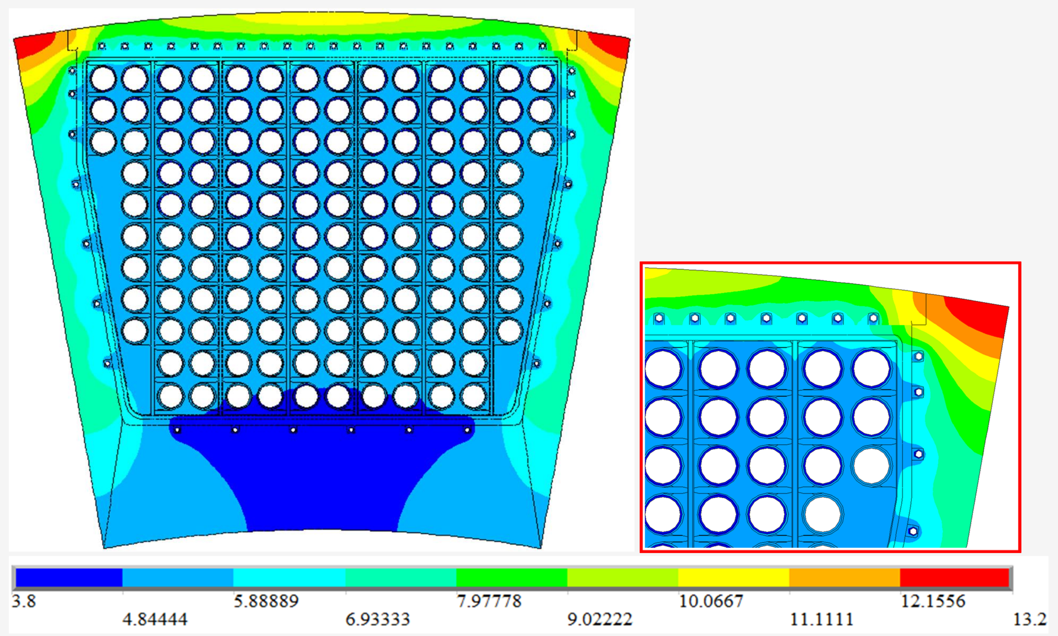
The analysis finishes when the bulk temperatures converge to a final value, i.e. when the maximum percentage difference between the bulk temperatures of two subsequent iterations is lower than 0.1 %.

Furthermore, a preliminary transient analysis has been performed only for the Pancake Wound configuration, with the assumption of neglecting both the heat load due to plasma instabilities and the heat exchange between the two internal regions inside the CICCs.

PANCAKE WOUND

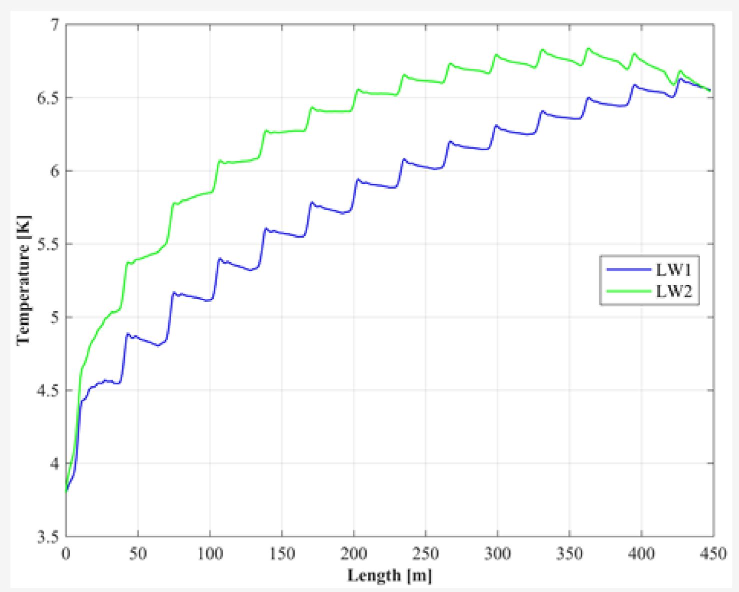


Temperature profiles in bundle and hole regions along pancake #2

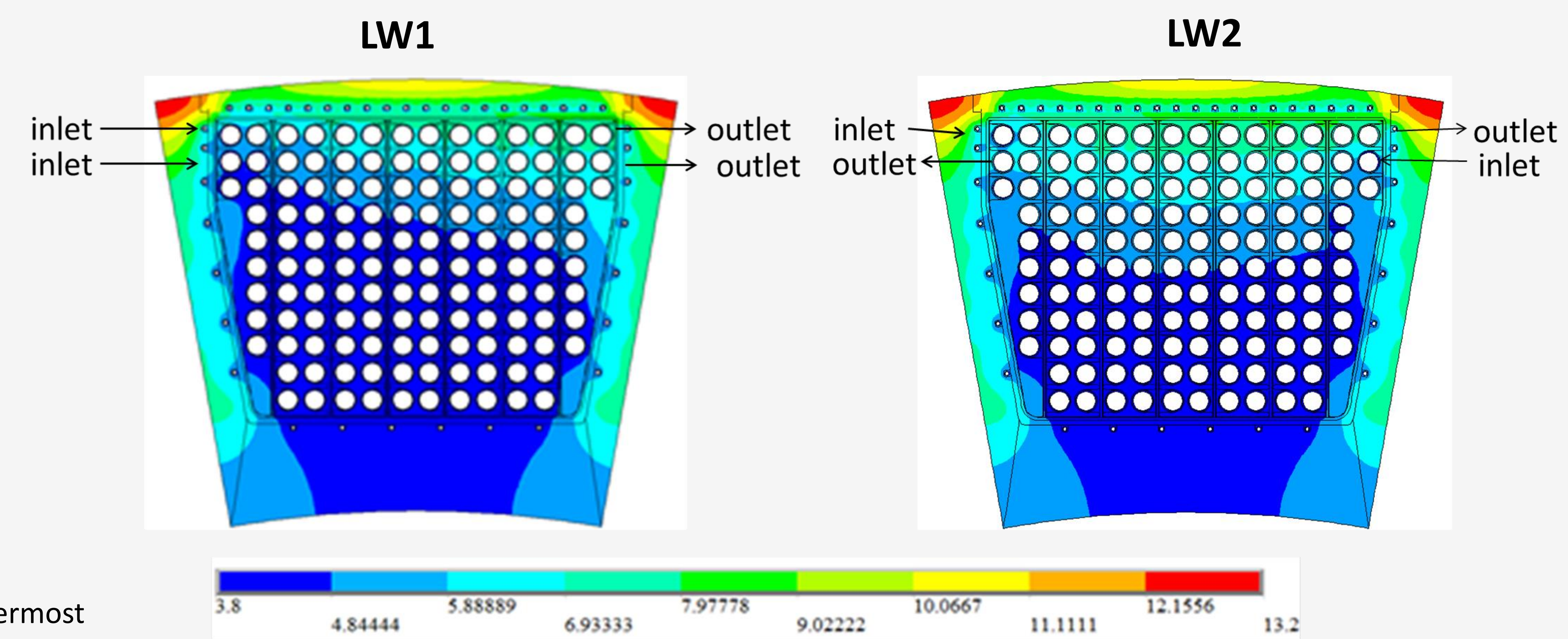


Temperature map in the most loaded segment (section #5) for PW layout

LAYER WOUND

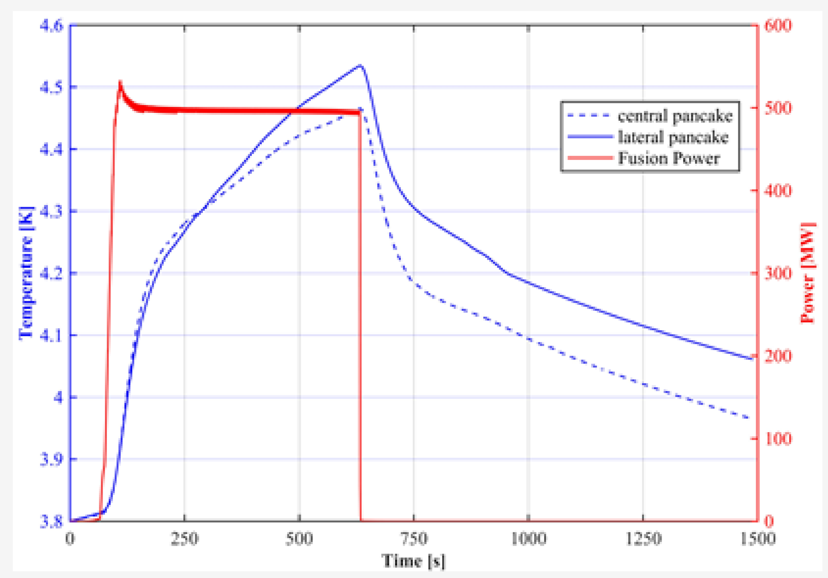


Helium temperature profile in bundle region along the innermost layer of the two configuration LW1 and LW2.



Temperature maps in the section #5 for LW 1 (left) and LW 2 (right).

PRELIMINARY TRANSIENT



Variation of Helium temperature during ramp up, burn, ramp down and dwell in the innermost turn of central and lateral pancakes of section #2