Experimental characterization of the ITER TF structure cooling in HELIOS test facility

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Abstract. During ITER plasma operation, large thermal loads are generated in the stainless steel Toroidal Field (TF) coil casing. To minimize the impact on the temperature of the TF Cable in Conduit Conductor (CICC), these heat loads are intercepted by case cooling channels which are implemented at the interface to the winding pack. One of the design options for the case cooling channels consists of a stainless steel pipe inserted in a rectangular groove which is machined in the casing and filled by a charged resin of high thermal conductivity. A higher number of cooling pipes is arranged at the plasma facing wall of the case, thus providing a better shielding to the TF conductor at high field. To assess the efficiency of the cooling pipes and their thermal coupling with the charged resin, experimental characterizations have been performed. First of all, the thermal resistance vs temperature of some of the individual components of a TF coil has been measured on representative samples in a cryogenic bench. Further characterizations have been performed on an integrated mock-up of the TF cooling scheme at cryogenic temperature in HELIOS test facility at CEA Grenoble. The mock-up consists of a piece of TF casing that can be heated uniformly on its surface, one cooling channel implemented in the groove which is filled with the charged resin, the filler, the ground insulation, the radial plate and one insulated CICC. The cooling pipe and the CICC are cooled by supercritical helium at 4.4 K and 5 bar; the instrumentation consists of temperature, pressure and mass flow sensors. Both stationary and transient operating modes have been investigated to assess the thermal efficiency of the case cooling design. The experimental tests are presented and the first results are discussed and analyzed in this document.

1. Introduction

CEA French Alternative Energies and Atomic Energy Commission
CICC Cable In Conduit Conductor
GKG Glass Kapton Glass
HELIOS Helium Loop for High Load Smoothing

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The local efficiency of the cooling pipe to extract the heat deposited in the TF casing has been investigated in the past to estimate the required equivalent heat transfer coefficient during a 15 MA ITER plasma reference scenario and also during plasma disruption and fast discharge [1]. The overall assessment of the thermal efficiency of the cooling layout of TF structure depends on the thermal conductivities of the materials involved in the layered structure and also on the manufacturing processes. The cooling pipes in stainless steel are inserted in rectangular grooves filled with a charged resin to ensure an acceptable thermal contact. The cooling pipe layout is designed to extract most of the loads deposited in the structure. A thermal barrier is composed of a gap filler, the ground insulation and finally the radial plate in order to minimize the heat loads transferred to the insulated CICC (Figure 2). A homogeneous and complete impregnation of the resin in the grooves is indeed crucial. Neither crack nor defaults shall occur during manufacturing and integration processes, or during the cool down and warm-up cycles to ensure a good and long lasting thermal coupling. A dedicated mock-up of 1 meter has been manufactured to characterize thermal coupling between the TF casing and the TF CICC (Figure 1). Experimental cryogenic tests have been performed in HELIOS test facility [2], which was modified in order to integrate the mock-up and to assess the overall cooling capacity of the TF casing with supercritical helium flow at 4.4 K and 5 bar. Thermo-hydraulic simulations in quasi-3D with the code Venecia [3] have been conducted with several assumptions on the charged resin conductivity in order to compare and analyze the experimental data.

2. Charged resin conductivity

Various insulation materials have been characterized down to 4.4K in a thermal conductivity cryogenic bench at CEA Grenoble [4]. Figure 3 shows three conductivity measurements for the G10, the dolomite and the TF conductor turn insulation, also named GKG, a Glass Kapton Glass fiber sandwich impregnated with cyanate-ester resin. The ground insulation is also made of GKG. As for the charged resin’s thermal conductivity, a target value of one to two times the dolomite is expected to help extracting heat in case a fast event such as plasma disruption generates heat deposition in the casing.
Several sandwich samples have been tested (TF turn insulation glued in between two parts of stainless steel, see Figure 4 for example) and reveal that the thermal contact resistance of the glue joint is negligible [4].

![Figure 3. Comparison of individual materials’ conductivity measurements on a cryogenic test bench [4].](image)

![Figure 4. L2P1 stainless steel sandwich with fiber glass impregnated by cyanate-ester: the resin thickness equals to: 4.24 mm.](image)

3. Experimental set-up

3.1 Mock-up description

The TF structure mock-up installed in HELIOS is one meter long and is composed of a CICC and a stainless steel cooling pipe, thermally coupled with a layered structure of different materials (Figure 1). Its manufacture is split into two main items, the conductor/radial plate subassembly and the final impregnation and assembly.

3.2 Conductor/radial plate subassembly

As conductor the archival sample of conductor length 80KAN009 is made of Cu strand only. The central channel has been blocked by means of an epoxy rod of 7.8 mm diameter. The turn insulation consists of 7 layers: 1 glass + 3 GKG + 3 glass layers. The ground insulation has been wrapped over the insulated conductor and radial plate piece. In total 12 layers (2 glass + 8 GKG + 2 glass) have been applied to match the required thickness of 6 mm. The impregnation (VPI technique) of the turn and ground insulation was done in one step using the ITER TF reference resin “cyanate-ester”.

3.3 Final impregnation and assembly

Before impregnating the casing block with the conductor/radial subassembly the cooling pipe was installed into the groove of the casing block. This work was made at RAL, UK, who was in charge of developing the charged resin NYCO Wollastocoat [5] providing thermal connection between the steel block and the cooling pipe. The final impregnation (VPI technique) of the two subassemblies was done using dolomite as gap filler material.
3.4 Integration in HELIOS test facility

The mock-up has been equipped with surface heaters with a uniform density of about 0.035 W/cm² on the lateral surfaces and the top face corresponding to the plasma facing surface (Figure 1). Total deposited power ranges from 0 to 50 W. Cernox thermometers are located at the inlet and outlet of both CICC and cooling loop lines (Figure 5). A thermometer is also glued on the surface of the TF structure at the middle of the mock-up in between two adjacent thermofoil heaters. The mock-up has been insulated with MLI (multi layer insulation) and integrated into the HELIOS loop driven by a cold circulator. The loop is thermally coupled to 2 heat exchangers immersed in a saturated liquid helium bath.

Figure 5. TF structure mock-up with temperature sensors and heaters.

Figure 6. Simplified scheme of HELIOS with mock-up.
bath, in order to extract heat deposited on the loop (Figure 6). The helium supply flows at about 4.4 K and 5 bar through three parallel lines: cooling pipe line, CICC line and by-pass line to ensure a nominal operation of the loop at about 40 g/s. The nominal flows in the CICC and the cooling loop are 2.4 g/s in both channels. The lines are instrumented with venturi flowmeters and pressure sensors. The static heat losses on the loop between the first heat exchanger and the second one have been estimated during a calibration test at about 30 W. The simplified process diagram is shown on Figure 6.

4. Transient scenarios with 30 W heat deposition

4.1 Operating conditions to reach 30W in steady state

The cooling pipe and the CICC bundle have been tested in nominal plasma operating conditions with 2.4 g/s in both channels. For the CICC, it corresponds to the nominal mass flow of the TF conductor bundle region only, as the central channel is plugged. The initial inlet pressure is about 4.6 bar and the inlet temperature is 4.7 K. At \( t = 0 \) s, a 30 W load is applied on the TF structure and steady state is reached in about 2000 s. The experimental evolutions in pressure, mass flows, helium and TF casing temperatures have been compared to simulations by the Venecia code [3]. The assumptions for materials and their properties have been summarized in Table 1.

| TF structure regions | Materials [3] | Geometry |
|----------------------|--------------|----------|
| Casing               | Stainless steel | Height 66.8 mm * 40 mm |
| Cooling tube         | Stainless steel | OD=10.5 mm |
|                      |              | Thickness=1.2 mm |
| Charged resin        | GKG or 2xDolomite | Rectangular groove: 13.5 |
|                      |              | (depth) * 12.5 mm (width) |
| Gap filler           | Dolomite     | 11 mm |
| Ground insulation    | GKG          | 6 mm |
| Radial plate         | Stainless steel | 30.7 mm (from CICC center) |
| TF insulator         | GKG          | 1.85 mm |
| CICC jacket          | Stainless steel | OD = 43.7 mm |
|                      |              | Thickness 2 mm |

4.2 Results and comparison with simulations

Calibrations of the venturi flow-meters were performed with thermal heat balance calculations and could give good accuracy of mass flows with a reasonable value of +/- 5%. Enthalpy balance calculations lead to the following estimated percentages of the heat extracted between the cooling pipe and the CICC: 97% for the cooling pipe versus 3% for the CICC. The highly unbalanced heat removal emphasizes the very low contribution of the CICC in the cooling of the TF structure, for which the measurement uncertainty is non-negligible (small temperature gradient). The current thermal modelling with GKG as charged resin in the cooling pipe groove and the assumptions would lead to a repartition of 86% in the cooling pipe and 14% in the CICC. This repartition is mainly driven by the thermal barrier. Any uncertainty on thermal barrier heat transfer, would infer a change in the heat repartition, and could explain the experimental results with a higher expected thermal insulation of the layered material structure between the TF structure and the CICC.
The loop is configured in isochoric mode, i.e. in closed loop with a constant helium inventory stored in about 13 L of circulating helium. With this helium volume configuration, the 30 W injected heat induces a pressure increase of about 2 bar (from 4.6 to 6.5 bar in Figure 7): the experimental transient evolution has a longer time constant (872 s) to reach 95% of the steady state value compared to the simulation with 2xDolomite (610 s). The experimental time constant is close to the one simulated with GKG (975 s, see Table 2).
For the CICC line, the experimental inlet and outlet temperature evolutions (Figure 10) show temperature increase from 4.7 K to respectively 4.75 K and 4.8 K, smaller than the expected simulated values with 2xDolomites and GKG. It is related to the underestimation of the fraction (around 3%) of heat flux through the CICC line, which can be explained by a higher insulation of the thermal barrier, due to possible degradations during the processes which have to be investigated. For the cooling pipe (97% of the heat flux), the transient shape of the outlet temperature (Figure 11) is a signature of the heat transfer through the TF structure, independently of steady state values, reached after about 2000s. The experimental curve fits better the simulation with GKG, however with a slightly shorter time constant. Hence, the apparent thermal efficiency of the cooling pipe is closer to the GKG resin material properties. As for the helium outlet temperature, the experimental TF structure increase seems to better follow the simulation curve with GKG, with a slightly longer time constant (Figure 12).
5. Conclusion and perspectives
The thermal efficiency of the TF cooling layout has been investigated on a representative mockup featuring one of the design options for the case cooling channels. In transient regime, the variations of pressure, mass flow and temperatures are dependent on the overall thermal coupling: both the thermal barrier of the layered structure between the TF structure and the CICC but also the thermal coupling of the charged resin impact the variation of the above parameters vs time. The helium outlet temperature of the cooling pipe is a good signature of the overall thermal efficiency of the charged resin. Comparisons between experimental data and simulations based on thermal properties of various material suggest that the apparent thermal conductivity of the charged resign would be rather close to the GKG material, at about 0.04-0.08 W/(mK), in the range 10-20 K. This experimental characterization gives a global efficiency lower than expected. This could be caused by a combination of various effects: the intrinsic thermal conductivity of the charged resin, the homogeneity of the impregnation along the 1 meter length of the mock-up, defects in the impregnation, cracks in the resin during the manufacturing process or during the cool down, etc. The individual contribution of each of the effects above is difficult to quantify, and shall be mitigated during future manufacturing processes. An autopsy of the tested mockup is expected to clarify the matter. Further analyses will be performed to confirm the overall cooling efficiency as other transient scenarios have been investigated.

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