Helium Flow and Temperatures in a Heated Sample of a Final ITER TF Cable-in-Conduit Conductor

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Abstract. The quest for a detailed understanding of the thermo-hydraulic behaviour of the helium flow in the dual-channel cable-in-conduit conductor (CICC) for the ITER toroidal-field coils led to a series of experiments in the SULTAN test facility on a dedicated sample made according to the final conductor design. With helium flowing through the conductor as expected during ITER operation, the sample was heated by eddy-current losses induced in the strands by an applied AC magnetic field as well as by foil heaters mounted on the outside of the conductor jacket. Temperature sensors mounted on the jacket surface, in the central channel and at different radii in the sub-cable region showed the longitudinal as well as radial temperature distribution at different mass flow rates and heat loads. Spot heaters in the bundle and the central channel created small heated helium regions, which were detected downstream by a series of temperature sensors. With a time-of-flight method the helium velocity could thus be determined independently of any flow model. The temperature and velocity distributions in bundle and central channel under different mass-flow and heat load conditions thus led to a detailed picture of the helium flow in the final ITER TF CICCs.

1. Introduction
Experiments several years ago [1] showed that a downward helium flow in a dual-channel cable-in-conduit conductor (CICC) may be reversed in the 'bundle' region, where the strands are located, if the heat load on the conductor is sufficiently large. An increased downward flow in the central channel maintains the total, usually imposed, helium mass flow. Different helium densities in the two channels, resulting from temperature variations, lead to different gravity and buoyancy forces and thus the observed flow velocity reversal, which may be stationary or oscillatory [2].

A 3.5 m long sample conductor allowed the measurement of the thermo-hydraulic behaviour in detail under a number of heat-load and mass-flow conditions. Particularly important for the dimensioning of the cryogenic system and the eventual operation of the coils are the maximum local temperatures, which occur usually just underneath the cable jacket. They exceed the average temperature in the cross-section and thus reduce the temperature margin of superconducting strands there.

The investigated conductor, made according to the final design for the ITER toroidal-field (TF) coils, differs in the diameter of the central channel, the cable diameter, the void fraction of the cable and the twist-pitch lengths to a similarly measured conductor [3]. Improved locations of temperature sensors, foil heaters and spot heaters permit the observation of more detail in the temperature and flow velocity distributions at various operating conditions.
Figure 1. Layout of the sample (left) and cross-sections with installed temperature sensors and spot heaters (right). Spot heaters in the central channel: SHc××, in the bundle: SHb××. T sensors in central channel, bundle and below the jacket: TSc××, TSb×× and TSj××. Foil heaters on the outer jacket surface: H× with different length. T sensors on outer jacket surface and on sub-cable 1: TS×, opposite sub-cable 1: TO× (shown as black dots; the × is a place holder for a single letter or digit). Sensors or heaters mentioned in the text are highlighted.
2. Experimental

2.1. Sample preparation

Table 1 lists major properties of the CICC manufactured according to the final ("Option II") ITER TF conductor layout. Because previous experiments showed that the helium flows primarily along the six sub-cables, the spiral path of one ("Sub-cable 1") was marked on the outside of the jacket to install the majority of sensors along it (see figure 1). In the subsequent heat treatment at ~650 °C the Nb3Sn strands became superconducting so that the induction of AC loses during the experiments could create heat in the bundle homogeneously. After the treatment technicians welded Swagelok® flanges along Sub-cable 1 for the carriers holding the temperature sensors inside the cable (see figure 1 and 3: TS×××; Here × is a place holder for a single letter or digit) as well as for the spot heaters (SH×××, 500 Ω, 1/8 W). They attached the foil heaters H1 to H8 to the jacket using a wrap of woven glass-fibre tape and epoxy resin and mounted the temperature sensors on the outside of the jacket along Sub-cable 1 (TS×) as well as opposite this sub-cable (TO×), depending on the availability of space on the jacket surface and to obtain additional information.

Above and below foil heater H3 (co-located with the region where a copper coil of the SULTAN facility could generate an AC field) two sets of 7 sensors and spot heaters permitted the measurement of the local helium flow velocity in the central channel as well as in the bundle (see second drawing on the right in figure 1): With downward flowing helium a heat pulse in spot heater SHc3u, for example, creates a small region of helium with a temperature increased by a few hundredths of Kelvin, which

![Figure 2. Cross section of the used conductor. Photograph courtesy of ENEA Frascati.](image1)

![Figure 3. Photograph of a carrier for three internal temperature sensors placed on top of a conductor cross section. Sensors j are placed just underneath the jacket, sensors b in the bundle and sensors c close to the central cooling channel.](image2)

| Table 1: Characteristics of the used ITER TF cable |
|-----------------------------------------------|
| Superconducting strands | ø 0.82 mm, 2 µm Cr plating, Cu/nonCu = 1 |
| Sub cable | (2 sc + 1 Cu)×3×5×5 strands + 3×4 Cu core |
| Number of strands | Superconducting: 900, copper: 522 |
| Sub-cable wrap | Single layer 0.1 mm steel foil, ~50% coverage |
| Central spiral | Inner/outer ø 8/10 mm, 30% open surface |
| Final cabling stage | 6 wrapped sub cables, 429 mm twist pitch |
| Bundle void fraction | Average: 32.8 %, local: 29.7 % |
| Cable jacket | Inner/outer ø 39.6/43.6 mm, 316 LN steel |
flows towards spot heater TSc3u, 35 mm below, where the T pulse is first recorded, and further down to T sensor TSc3d, another 35 mm lower. The local flow velocity could be calculated from the delay between the two recorded T pulses. The hope that the delay between two temperature signals would be easier to compare than the one between the sharp spot-heater pulse to a slightly spread T-sensor signal was somewhat dashed by the observed noise level (see section 4). Although less than 10 mK it made the analysis difficult and could not be filtered without losing important time resolution. Better signal conditioning or longer distances between sensors may improve this situation.

With all sensors and heaters wired up, edge profiles were attached to the sample to protect it and centre it in the SULTAN test well. Several layers of superinsulation wrapped around the conductor prevented any heat from entering or leaving the conductor in an uncontrolled manner.

2.2. Thermo-hydraulic measurements
After installation in the SULTAN test facility 10 bar super-critical helium, flowing from top to bottom, cooled the sample to 4.5 K. In about 30 experimental runs either the foil heaters on the jacket or the application of an AC magnetic field with a frequency between 0.2 and 5 Hz deposited heat on conductor sections in steps to study the resulting temperature response in the helium flow with all the installed sensors. Only stationary conditions were investigated to facilitate the analysis. A feedback loop of the SULTAN facility regulated the total mass flow rate \( \dot{m} \) to 4, 6, 8 or 10 g/s. Four-second pulses on spot heaters SHc3u and SHc4u generated the small regions with increased temperatures for the determination of the flow velocity in the central channel.

3. Stationary temperature profiles
3.1. Deviations from a homogeneous temperature distribution in the cross sections
For dimensioning the cooling requirements of a CICC in a coil all the heat loads along the helium flow from inlets to outlets are added up and the parameters (cable layout, \( \dot{m} \), \( \Delta p \), etc.) set to obtain an acceptable temperature at the outlet. The temperature profile along the conductor is thereby calculated with the one-dimensional enthalpy equation:

\[
h_n = h(T_{in}, P_{in}) + \frac{1}{\dot{m}} \frac{\partial Q}{\partial t}, \quad T_n = T(h_n, P_n)
\]
Here the enthalpy per unit mass of the helium \( h_n \) at cross section \( n \) is calculated from the inlet enthalpy, the mass flow rate \( m \dot{\mathbf{v}} \) and the heat deposition rate \( \delta Q/dt \) from inlet to cross section \( n \). With the inverse enthalpy function \( T(h, p) \) the average temperature at cross section \( n \) is readily obtained. For the analysis and understanding of the current experiments it is useful to compare the temperatures measured with a sensor at a particular location with the expected 1D temperature at this cross section:

\[
\Delta T = T_n\text{(measured)} - T\left(h_n, p_n\right)
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\]

A coil designer knowing the maximum deviations from the 1D expectations \( \Delta T_{\text{max}} \) under all occurring conditions, may consider these to get a more accurate picture of the temperature margin of the superconducting strands throughout the coil.

### 3.2. Temperature profiles

Figures 4, 5 and 6 show measured temperatures on the jacket surface (■), underneath the jacket (▼), in the bundle (▲) and in the central channel (●) for heat deposition rates of about 12.5 W, generated by induced AC losses, foil heater H3 and foil heater H6 respectively. The grey line shows the expected profile if the temperatures were homogeneous in each cross section. The temperatures on the jacket surface exceed the 1D expectation by up to 0.36 K just downstream of the heated region. The deviation is smaller for the more uniform AC heating than for the foil heaters acting through the jacket wall. Because sensor TS6 is closer to heater H6 than TO3d to H3, the deviation at the former sensor is larger than at the latter. In the central channel, on the other hand, the temperature is smaller than the average temperature, as expected. Interestingly – and fortunately for the coil operation – the differences \( \Delta T \) disappear rapidly downstream of a heated region. The \( \Delta T \) decay length \( \lambda \) is characteristic for the mixing of the flow of helium in the bundle and the central channel [3, 4].

Figure 7 shows jacket temperature profiles for different power levels in heater H6 at the lower mass flow rate of 4 g/s. At low power (2, 6, 12 W) the upstream temperature remains lower than the downstream temperature; at 20 W, corresponding to the high heat deposition rate per unit length of 52 W/m, the two temperatures are equal, clearly indicating that the helium flow underneath the jacket stagnates [2]. At even higher power levels the helium flow reverses, the deposited heat is transported upwards and eventually removed downwards by the cooler helium in the central channel, where the flow velocity increases (with a constant total mass flow imposed). The shape of the profiles suggests that the temperatures underneath the foil heater, the location of which is marked by the yellow area, are higher than the ones measured by the adjacent sensors. It is also noteworthy that in this rather
In an extreme situation the flow pattern is not radially symmetric any more: more heat is transported upwards by Sub-cable 1 than by the opposite one, as the higher temperatures at TS7 and TS8 relative to TO7 and TO8 show (for clarity only shown for 75 W). Small asymmetries in the stranding of the cable may cause this effect.

The different mixing behaviour is apparent in a logarithmic plot of $\Delta T$ (figure 8): up to 20 W the decay length $\lambda$ is practically constant (slopes of the curves downstream of H6), while above this level the differences disappear more rapidly since the central channel already transports most of the deposited heat. At double the mass flow rate no flow reversal in the bundle occurs, even at high power levels and the mixing length remains constant. The helium temperature underneath the heater is higher than the one measured at the ends (dotted lines).

![Figure 8](image)

**Figure 8.** At low power levels the central-channel-bundle mixing length downstream of H6 is about 37 cm; above 20 W it becomes smaller because most of the heat is transported upwards where it eventually ‘mixes’ into the central channel.

![Figure 9](image)

**Figure 9.** At a mass flow rate of 8 g/s no flow reversal in the bundle occurs, even at high power levels and the mixing length remains constant. The helium temperature underneath the heater is higher than the one measured at the ends (dotted lines).

![Figure 10](image)

**Figure 10.** The observed $\Delta T$ decay lengths at the jacket surface downstream of the region heated by AC or H3 at different mass-flow rates. Interestingly $\lambda$ is constant for H3 heating, while it slightly increases with mass flow and decreases with power for AC heating. Below the dashed orange line flow reversal occurs.

![Figure 11](image)

**Figure 11.** The observed $\Delta T$ (relative to the 1D model) at sensor TO3d as a function of heat deposition per unit length (All heaters, H3 or AC) and per mass flow rate. With the ITER-relevant AC heating and at low power levels, $\Delta T$ scales linearly, indicating that the flow patterns remain comparable when heating $(dP/dz)$ and ‘cooling’ $(\dot{m})$ are increased proportionately.
3.3. Scaling of the mixing length and temperature deviation magnitude.

In the studied stationary helium flow states in an ITER TF CICC cooling by the imposed helium mass flow and heat deposition reach equilibrium to establish a stationary temperature distribution. To see if an increase in cooling \(\dot{m}\) and a proportional rise of heating lead to similar temperature profiles, the two characteristic parameters describing the profiles, \(\lambda\) and \(\Delta T\) at a given location (ideally where \(\Delta T\) is maximal), were plotted as a function of the heat deposition per unit length of conductor \((dP/dz)\) divided by the mass flow rate \(\dot{m}\) (figures 10 and 11). Although the total deposited heat per unit time \((P)\) determines the temperature at the end of a heated region (equation (1)), the power per unit length has the strongest impact on the temperature inhomogeneity within a cross section \((\Delta T)\).

Figure 10 shows that the mixing length \(\lambda\) is remarkably independent of \(\dot{m}\) as well as \(dP/dz\), remaining in the range of 30 to 43 cm under all conditions studied. When AC losses deposit heat at low power the mixing length reaches more than 60 cm, possibly because the temperature differences are small. For \(\Delta T\) the situation is inverse: Here the deviations from the 1D average temperature scale very well up to high deposition rates. The \(\Delta T\) values observed at TO3d lie on a line with a slope of 43 mKgm/J \((\Delta T[(dP/dz)/\dot{m}])\) for AC heating, of 63 mKgm/J for heating with H3 and a slope of 110 mKgm/J if all heaters are powered simultaneously with the same \(dP/dz\). Because it is homogeneous in the bundle AC heating generates the smallest radial \(T\) variation. Heating with all heaters or only one apparently creates different He flow patterns leading to a higher radial \(T\) variation in the former case. The temperature gradient across the wall thickness of the jacket has no influence because the chosen sensor TO3d is sufficiently far downstream of heater H3. The readings were also confirmed by sensor TSj3d, mounted in the helium just underneath the jacket.

A first assessment of \(\Delta T\) for a given mass flow rate and heat deposition power can be obtained by multiplying a slope value with \(dP/dz\) and dividing it by \(\dot{m}\). 110 mKgm/J is a conservative value, while 43 mKgm/J may be too optimistic in situations where heat is deposited homogeneously in the bundle region over several meters.

4. Helium flow velocities in central channel and bundle

Small heat pulses created with spot heaters SHc3u and SHc4u leading to small regions of helium with slightly elevated temperature were used to measure the helium flow velocities in the central channel, as described above. Figure 12 shows the signals of the heater voltage and the temperatures recorded with sensors TSc3u and TSc3d. From the time delay between the onsets of the temperature pulses and the distance between the two sensors (35 mm) the velocity in the central channel was calculated and the one in the bundle region deducted from the total mass flow rate. Figure 13 shows that at \(\dot{m} = 4\) g/s

**Figure 12.** Recordings of temperature with sensors TSc3u and TSc3d and of the voltage of spot heater SHc3u. The vertical lines indicate the times taken to determine the delay between the TSc3u and TSc3d temperature pulses.

**Figure 13.** Helium flow velocity in the central channel and in the strand bundle region, the latter calculated from the former and the total mass flow rate.
the velocity in the channel is about 6.5 times higher than the average velocity in the bundle, while at 10 g/s this factor decreases to about 5. The flow partition thus depends on the velocity-dependent hydraulic impedance of the two linked helium channels. The relatively large error bars result from the difficulty of precisely determining the onset of the small temperature pulses with the observed noise levels.

5. Conclusions
The thermo-hydraulic measurements on an ITER TF conductor of the final design confirmed the observations on similar conductors: helium flowing in the bundle region mixes with helium in the central channel over a characteristic distance between 35 and 60 cm. At the expected heat deposition levels (per unit length) the temperature differences between the two regions and thus helium-density differences remain small and no gravity-driven flow reversal arises in the bundle region.

The measured $\Delta T$ at the jacket surface relative to the 1D expectation scales well with the heat deposition per unit length and the mass flow rate. It is therefore possible to predict local maximum temperatures from known (or expected) heat deposition profiles and the mass flow rate. $\Delta T$ remains well below 50 mK for the conditions expected in ITER ($dP/dz \sim 1.6$ W/m, $m > 8$ g/s).

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