Cryogenics xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Using the HELIOS facility for assessment of bundle-jacket thermal coupling in a CICC

B. Lacroix [a,*], B. Rousset [b], H. Cloez [a], P. Decool [a], J.L. Duchateau [a], C. Hoa [b], N. Luchier [b], S. Nicollet [a], F. Topin [c]

[a] CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[b] CEA, INAC, SBT, F-38054 Grenoble, France
[c] Aix Marseille Université, CNRS, IUSTI UMR 7343, 13453 Marseille, France

ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form 15 May 2016
Accepted 22 May 2016
Available online xxxx

Keywords:
Cable-In-Conduit Conductor
Thermo-hydraulics
Fusion magnets
Heat transfer coefficient

ABSTRACT

In a Cable In Conduit Conductor (CICC) cooled by forced circulation of supercritical helium, the heat exchange in the bundle region can play a significant role for conductor safe operation, while remaining a quite uncertain parameter. Heat exchange between bundle and jacket depends on the relative contributions of convective heat transfer due to the helium flow inside the bundle and of thermal resistance due to the wrappings between the cable and the conduit.

In order to qualify this thermal coupling at realistic operating conditions, a dedicated experiment on a 1.2 m sample of ITER Toroidal Field (TF) dummy conductor was designed and performed in the HELIOS test facility at CEA Grenoble. Several methods were envisaged, and the choice was made to assess bundle-jacket heat transfer coefficient by measuring the temperature of a solid copper cylinder inserted over the conductor jacket and submitted to heat deposition on its outer surface.

The mock-up was manufactured and tested in spring 2015. Bundle-jacket heat transfer coefficient was found in the range 300–500 W m^{-2} K^{-1}. Results analysis suggests that the order of magnitude of convective heat transfer coefficient inside bundle is closer to Colburn–Reynolds analogy than to Dittus–Boelter correlation, and that bundle-jacket thermal coupling is mainly limited by thermal resistance due to wrappings. A model based on an equivalent layer of stagnant helium between wraps and jacket was proposed and showed a good consistency with the experiment, with relevant values for the helium layer thickness.

1. Introduction

In Cable In Conduit Conductors (CICCs) cooled by forced circulation of supercritical helium (He), even if substantial work has been conducted for qualifying heat transfer mechanisms [1–4], notably in dual channel CICCs, the heat exchange in the bundle region remains a parameter still quite uncertain. The assessment of the convective heat transfer coefficient (HTC) between helium and strands (h_{bundle}) can widely vary depending on the correlation taken into account (typically Dittus–Boelter correlation versus Colburn–Reynolds analogy), while modelling the thermal coupling between bundle channel and jacket (h_{jacket}) requires estimating not only h_{bundle} but also the thermal resistance due to the wrappings between the cable and the conduit. Heat exchange between bundle and jacket is also affected by the flux repartition between:

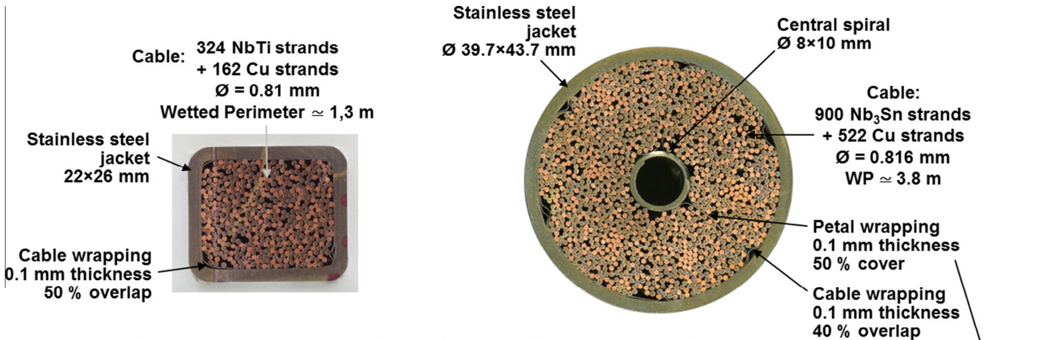
- direct heat transfer between He and wall (wall corresponds to jacket or wrappings, and usually corresponds to wrappings exclusively, due to cable wrap overlap as shown in Fig. 1),
- and heat transfer through the strands in contact with the wall.

This approach is sometimes proposed in codes dedicated to CICCs thermo-hydraulics [5]. It requires providing the surface of strands in contact with the wall and the related thermal resistance, which are parameters difficult to estimate. In the present study, it was preferred to model heat transfer between bundle and jacket through a single surface (inner jacket surface) and a single mean heat transfer coefficient h_{jacket} integrating all heat transfer processes: both thermal exchanges described above, as well as contact thermal resistances induced by wrappings.

Heat exchanges between strands and He and between cable and jacket, described through h_{bundle} and h_{jacket} respectively, can impact the conductor behaviour, as they affect thermal stability, quench propagation velocity and hot spot temperature. In particular, the potentially major role of the conduit on hot spot temperature

* Corresponding author.
E-mail address: benoit.lacroix@cea.fr (B. Lacroix).

http://dx.doi.org/10.1016/j.cryogenics.2016.05.007
0011-2275/



L pancake	114 m
S NbTi	56.8 mm²
S Cu	180 mm²
B	5.6 T
Top	5 K
ΔTma	1.2 K
Iop	25.7 kA

JT-60SA TF conductor

L pancake	380 m
S nonCu	235.3 mm²
S Cu	508 mm²
B	11.8 T
Top	5 K
ΔTma	0.7 K
Iop	68 kA

ITER TF conductor

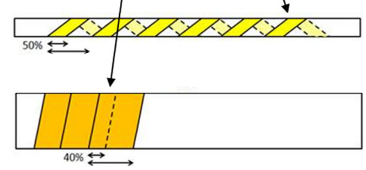


Fig. 1. Main characteristics of JT-60SA and ITER TF conductors.

suggests that the thermal coupling between the cable and the jacket can play a significant role for the conductor safe operation. On the opposite, in normal operation, h_{bundle} and h_{jacket} values have little impact on temperature margin, as temperature remains in the range where He enthalpy dominates that of materials.

2. Sensitivity of CICC thermo-hydraulic behaviour to h_{bundle} and h_{jacket}

2.1. Which models for h_{bundle} and h_{jacket}

In order to quantify the relative impacts of h_{bundle} and h_{jacket} on the thermo-hydraulic behaviour of a CICC, simulations were performed on JT-60SA TF conductor, whose main characteristics are presented in Fig. 1, together with ITER TF conductor. JT-60SA TF conductor was chosen for this preliminary study because it features no central spiral channel, thus facilitating the assessment of the respective roles of bundle cooling and of bundle-jacket thermal coupling on above mentioned phenomena (thermal stability, quench propagation and hot spot temperature). Several simulations were performed with the GANDALF code [5], considering the nominal mass flow rate of 3.5 g/s and fixed boundary conditions (T_{inlet} = 4.5 K, P_{inlet} = 5 bar, P_{outlet} = 3.93 bar).

Two correlations were considered for the bundle turbulent heat transfer coefficient, either the Dittus–Boelter (DB) correlation ($Nu_{\text{turb}} = 0.023\ Re^{0.8}\ Pr^{0.4}$) or the Colburn–Reynolds (CR) analogy between heat transfer and fluid friction ($Nu_{\text{turb}} = f/8\ Re\ Pr^{1/3}$ where f is the Darcy friction factor). A lower limit of $Nu_{\text{lam}} = 4$ was introduced, in order to take into account the Nusselt number for laminar flow in a pipe at low Re.

Dittus–Boelter and Colburn–Reynolds correlations are equivalent in case of a smooth tube, but for the JT-60SA TF conductor, they give respectively h_{bundle} = 710 and 2750 W m^{-2} K^{-1} at nominal operating conditions (Q = 3.5 g/s, T_{op} = 5 K, P = 5 bar, $Re \simeq 3500$). The factor of near 4 between the two values reflects the fact that the bundle friction factor is almost 4 times larger than the equivalent smooth tube (featuring the same hydraulic diameter). This order of magnitude of discrepancy can be observed on any CICC bundle channel, at similar compaction levels (bundle void fraction ≃ 30%).

Fig. 2 shows h_{bundle} values obtained with both DB and CR correlations for JT-60SA TF cable. The difference between both curves illustrates the difficulty for choosing a reliable correlation for h_{bundle}. The Colburn–Reynolds analogy is very convenient as it switches evaluation of heat transfer coefficient to accessible friction factor data. But due to the complex geometry, there are doubts whether these correlations are suitable for flow in CICC bundle region [2].

The choice of a model for the heat transfer coefficient between the bundle and the jacket is even more delicate, due to the presence of the stainless steel wrappings. Hereafter, for the JT-60SA TF conductor, the wrappings thickness (0.2 mm) was integrated in the jacket cross section, and the additional thermal resistance induced by wrappings was modelled as a layer of stagnant He, $R_{\text{th wraps}} = \frac{t_{\text{He layer}}}{\lambda_{\text{He layer}}(T)}$ (the dependence of He thermal conductivity λ_{He} on temperature was taken into account). For assessing the He layer thickness $t_{\text{He layer}}$, the cross section area of trapped He (estimated at 2 mm^2 by measurements) was assumed uniformly distributed around jacket inner perimeter, thus constituting a 26 μm layer of static He between the bundle and the conduit.

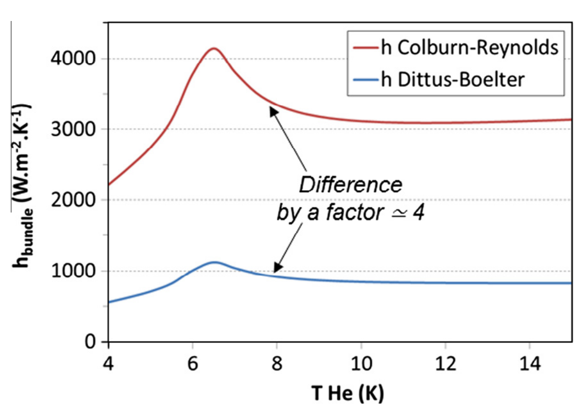


Fig. 2. Convective heat transfer coefficient in JT-60SA TF conductor (QHe = 3.5 g/s, P = 5 bar).

Please cite this article in press as: Lacroix B et al. Using the HELIOS facility for assessment of bundle-jacket thermal coupling in a CICC. Cryogenics (2016), http://dx.doi.org/10.1016/j.cryogenics.2016.05.007