Cryogenics 73 (2016) 91–100

Contents lists available at ScienceDirect

Cryogenics

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

Transverse heat transfer coefficient in the dual channel ITER TF CICCs. Part III: Direct method of assessment

Monika Lewandowska [a,*], Leszek Malinowski [b]

[a] Institute of Physics, Faculty of Mechanical Engineering and Mechatronics, West Pomeranian University of Technology, Szczecin, Al. Piastów 48, 70-311 Szczecin, Poland
[b] Faculty of Maritime Technology and Transport, West Pomeranian University of Technology, Szczecin, Al. Piastów 41, 71-065 Szczecin, Poland

ARTICLE INFO

Article history:
Received 5 July 2014
Received in revised form 16 April 2015
Accepted 4 July 2015
Available online 26 July 2015

Keywords:
Cable-in-conduit conductors
Heat transfer coefficient
Flow partition
Heat transfer correlation
Fusion magnets
ITER

ABSTRACT

The data resulting from the thermal-hydraulic test of the ITER TF CICC are used to determine the flow partition and the overall effective heat transfer coefficient (h_{BC}) between bundle and central channel in a direct way, i.e. by analysis of the heat transfer between both flow channels, based on the mass and energy balance equations and the readings of thermometers located inside the cable. In cases without a local heat source in the considered cable segment the obtained h_{BC} values were consistent with those obtained in earlier studies by analysis of experimental data using indirect methods. It was also observed that the transverse heat transfer was strongly enhanced in a cable segment heated from outside. This phenomenon results from the mass transfer from the bundle region to the central channel. The experimental h_{BC} data obtained for the case without a heat source in the considered segment were also compared with those calculated using various heat transfer correlations.

1. Introduction

Dual-channel Cable-in-Conduit Conductors (CICCs), designed for the ITER TF (toroidal field), CS (central solenoid) and PF (poloidal field) coils, consist of an annular bundle of twisted superconducting strands and a central cooling channel, separated by a steel spiral, which are enclosed in a leak-tight steel jacket. The ITER CICCs are cooled by a forced flow of supercritical helium. Reliable modeling of the transverse heat transfer in the complex CICC geometry is crucial for the analysis of cooling, stability, and the quench behavior of the ITER magnets. In CICC models typically two coupled 1-D channels of flow are considered, which require the knowledge of friction factors for the central channel and for the bundle region, and the overall effective bundle-central channel heat transfer coefficient (h_{BC}). The bundle-central channel transverse energy transfer can involve various physical processes, namely: (i) thermal diffusion in a boundary layers accompanied by heat conduction through a wall (a spiral or sub-cable wraps), (ii) convective heat transfer through the fully open perforation, and (iii) mass transfer across the perforation. In the present analysis we make an attempt to separate the energy transfer due to the mass transfer and focus on the effective bundle-central channel heat transfer involving the first two mechanisms mentioned above.

Four indirect methods to determine h_{BC} values, based on fitting different simplified analytical models to experimental data, have been proposed in the literature [1–4]. However, h_{BC} values obtained with different methods for the same conductor differ by up to a factor of about 2, since they are affected by the assumptions of the models used for the interpretation of the experimental data [5]. Indirect method do not also allow to assess the role of the mass transfer between the two CICC regions in relation to heat transfer, so their use should be restricted to cases where the experimental situation can justify the assumption, that the bundle-central channel mass transfer is negligible, i.e. when the temperature (and density) difference between both channels of flow is small and there are no local heat sources within the considered cable region.

A simplified predictive correlation for h_{BC}, based on the Colburn-Reynolds analogy, has been proposed in [6]. The h_{BC} values calculated with this correlation agree relatively well with those obtained from experiments [1,7], however, it was shown in [8] that the Colburn analogy is not applicable for the flow in a central channel of CICCs. The h_{BC} of the ITER CICC was also studied using a CFD model [9], but the results were about 1.5–1.8 times larger than the highest h_{BC} values obtained from experiments [1–4,7]. It should be noted, however, that the case studied in [9] was different from those of [1–4,7]. In the CFD simulations of [9] a local source with a very large heating power (100 W distributed over the length of one spiral pitch), located within the region of interest, was used,

* Corresponding author. Tel.: +48 91 449 4405; fax: +48 91 449 41 81.
E-mail addresses: monika.lewandowska@zut.edu.pl (M. Lewandowska), leszek.malinowski@zut.edu.pl (L. Malinowski).

http://dx.doi.org/10.1016/j.cryogenics.2015.07.001
0011-2275/

Nomenclature

A_{BC}	heat transfer area, m^2
D_{CS}	cable space diameter, m
D_h	hydraulic diameter, m
D_{in}	inner diameter of a central spiral, m
D_{out}	outer diameter of a central spiral, m
$D_{particle}$	particle diameter in a porous medium, equivalent diameter of a spherical particle, –
F_{dead}	dead space in the porous matrix (sealed pores), –
f	Fanning friction factor, –
h	heat transfer coefficient, W/(m^2 K)
h_{BC}	overall effective bundle-central channel heat transfer coefficient, W/(m^2 K)
i	helium specific enthalpy, J/kg
k	thermal conductivity, W/(m K)
$\dot{m}_{total}$	total helium mass flow rate in a cable, kg/s
$\Delta\dot{m}$	mass transfer between the central channel and the bundle region, kg/s
Nu	Nusselt number, defined as $Nu = hD_h/k_{He}$, –
Nu_φ	seepage Nusselt number, defined as $Nu_\varphi = hD_{particle}/k_{He}$, –
p	pressure, Pa
P	wetted perimeter, m
$perf_{sp}$	gap fraction of the central spiral, –
$perf_{swr}$	gap fraction of the sub-cable wrap, –
Pr	Prandtl number, defined as $Pr = C_p\mu/k$, –
Re	Reynolds number, defined as $Re = \rho v D_h/\mu$, –
Re_φ	seepage Reynolds number, defined as $Re_\varphi = \rho v \varphi\, D_{particle}/\mu$, –
t_{sp}	spiral thickness (height), m
t_{swr}	sub-cable wrap thickness, m
T	temperature, K
T_{ref}	reference temperature at no heat deposition, defined by Eq. (1), K
T_∞	common outlet temperature of both channels of flow, K
u	standard uncertainty
z	coordinate along the conductor, m

Greek

α	helix angle of the central spiral, deg
φ	void fraction of the bundle region, identical to porosity, –

Subscripts

B	bundle region
C	central cooling channel
J	jacket
owr	outer wrap
ref	reference
S	strands
sp	spiral
swr	sub-cable wrap

whereas in [1–4,7] heaters located outside the region of interest and with much smaller powers were considered, so that the temperature rise in the cable was sufficiently small to justify the use of analytical models with constant thermophysical parameters and flow partition.

In the present work we use the data resulting from the thermal–hydraulic test of the ITER TF CICC [10] to obtain h_{BC} values in a direct way, i.e. by analysis of the heat transfer between both channels of flow, based on the mass and energy balance equations and the readings of thermometers located inside the cable. A similar approach is often used in literature to determine the heat transfer coefficients in heat exchangers (see e.g. [11]), but it has never been used yet to evaluate h_{BC} in a dual channel CICC.

2. Experimental setup

The ITER TF CICC prototype sample of the Russian Federation (TFS-07W1 conductor, in short TFS) underwent a series of thermal–hydraulic tests using supercritical helium (at nominal 4.5 K and 1 MPa) in the SULTAN facility at EPFL-CRPP PSI Villigen [10]. The complete characteristics of the TFS sample was presented in [7,10], whereas the conductor parameters relevant for the present analysis are compiled in Table 1 (we report in Table 1 also the characteristic of the TFPS, $PFIS_W$ and $PFIS_{NW}$ conductors discussed in Section 5). Fig. 1 shows the schematic layout of the instrumentation used in the SULTAN facility for the tests of the TFS conductor, relevant to the present analysis. More details, including the figure presenting how the temperature sensors were mounted, are given in [10]. In this experiment the sample did not carry current, since only the thermal–hydraulic behavior was studied. This gave the unique opportunity to install temperature sensors not only at the jacket surface, which is typically the case for conductor tests in SULTAN, but also inside the cable space. The temperature sensors located inside the cable space (TRax, TRbx and TRcx, x = 2, 3 or 5) allowed us to perform a direct analysis of transverse heat transfer within the cable.

During the measurements supercritical helium entered the sample from the top with the total mass flow rates $\dot{m}_{total}$ regulated to 4, 5, 6, 8, or 10 g/s. The power in one of the resistive foil heaters H2, H3 or H4 attached to the jacket surface increased stepwise (considered heating powers for each run are specified in Table 2). The length of each heater was 0.381 m. Each heating step lasted until a steady state was reached, indicated by constant readings of all thermometers. In our analysis we use the temperature data measured in steady state conditions to assess the overall effective transverse heat transfer coefficient according to the procedures described in Section 3.

3. Heat transfer analysis and h_{BC} evaluation

Our analysis is based on the energy and mass balance equations. We take into account the dependence of the helium enthalpy on pressure and temperature. The pressure gradient in the sample is assumed constant, while the inlet and outlet pressures are read from the experimental data. At no heat deposition temperature along the sample slightly increases due to the Joule–Thomson effect. We assume that this temperature rise can be approximated by a linear function

$$T_{ref}(z) = T_{in} + \gamma z, \tag{1}$$

where T_{in} is the temperature at the sample inlet, approximated by the T8 readings and the values of parameter γ for each considered mass flow rate are given in Table 3.

In the case where heater H4 was used, we assume that the flow partition between the bundle and the central channel remained constant within Segment 1 (see Fig. 2a). Thus, for this case the energy balance equations for Segment 1 can be written as

$$\dot{m}_B i(p_3, T_{B3}) + \dot{Q}_{J3} + \dot{Q}_{S3} = \dot{m}_B i(p_2, T_{B2}) + \dot{Q}_{BC} + \dot{Q}_{J2} + \dot{Q}_{S2}, \tag{2a}$$