Pressure Drop of the ITER PFCI Cable-in-Conduit Conductor

Claudio Marinucci, Pierluigi Bruzzone, Antonio della Corte, Laura Savoldi Richard, and Roberto Zanino

Abstract—**Pressure drop in the ITER PFCI cable-in-conduit conductor (CICC) has been measured at CRPP using pressurized water at room temperature. The PFCI conductor is a dual channel CICC and the coolant flows in parallel in the central channel and in the annular bundle region. In our experiment the flow in the central channel is blocked and the longitudinal friction factor of the annular bundle region is deduced from measurements of pressure drop and mass flow rate. Two conductor samples are investigated, one with and one without subcable/outer cable wraps. The results show that the wraps have a negligible effect on the friction factor, and that the Katheder correlation overestimates the actual friction factor.**

Index Terms—**Friction, fusion reactor, pressure measurement, superconducting cables.**

I. Introduction

The Poloidal Field Coil Insert (PFCI), developed for the International Thermonuclear Experimental Reactor (ITER), is being manufactured (2004) and is expected to be tested at JAERI in Naka (Japan) in 2005. The PFCI conductor is a NbTi dual-channel cable-in-conduit conductor (CICC): the coolant, forced flow supercritical helium at 4.5 K and 0.6 MPa, flows in parallel in the central channel (spiral) and in the voids around the strands (annular bundle region). A short sample of the PFCI conductor has been recently tested in the CRPP SULTAN facility in Villigen (Switzerland) [1].

The assessment of the maximum mass flow rate for CICC at a given inlet pressure (and hence the power load removal) requires the knowledge of the friction factor of the cable, which has been so far characterized mainly by its hydraulic diameter and void fraction. If experimental data are not available, (usually less accurate) friction factors can be predicted using correlations. This issue is particularly sensitive in dual-channel CICC where the knowledge of the two friction factors is important for assessing the repartition of the total mass flow rate.

Here we present and discuss an experiment whose goal is to determine the friction factor of the annular bundle region of the PFCI conductor. Our experimental device uses pressurized water at constant temperature, a method applied in similar measurements of the ITER Central Solenoid conductor at CRPP [2].

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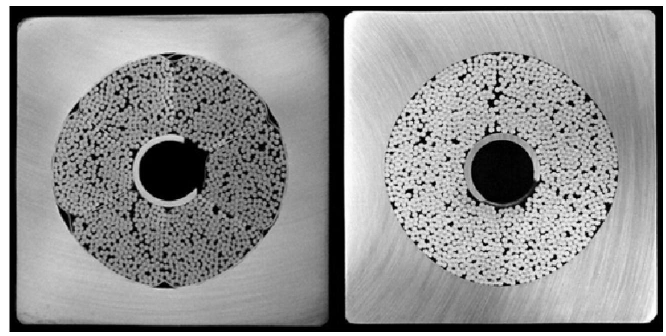

Fig. 1. PFCI NbTi forced flow cable-in-conduit conductors, with wraps (left) and without wraps (right). The two photos have slightly different scale, and the outer size of both conductors is given in the text.

II. Sample Layout and Experimental Set-Up

A. Sample Layout

Two straight conductor sections are investigated in the same experimental set-up; one is the original conductor with subcable and outer cable wraps (referred to as PFI_W), and the other is a conductor where these wraps have been removed (PFI_{NW}). Conductor cross sections are shown in Fig. 1.

De-wrapping is done by fixing one end of the conductor by a hose clamp, and the other end by the brazed pulling copper cap. The outer stainless steel wrap is removed first, then the subcable wraps. After the de-wrapping operations, the cable is partially reshaped by hand and finally inserted in the jacket with a pulling force not exceeding 19 000 N. In order to maintain the same bundle void fraction, the jacket of PFI_{NW} is compacted more than the jacket of PFI_W. A dimensional check, made on short sections cut by electronic erosion, shows that the final outer size is 49.82 × 49.78 mm in PFI_{NW} and 50.35 × 50.45 mm in PFI_W.

The geometrical parameters are listed in Table I. The PFCI conductor is made up of 6 subcables (n_{sub}) with a total of 1440 NbTi strands (n_{st}) of 0.73 mm diameter (d_{st}). We assume the mean twist angle, estimated by analogy from twist pitch measurements, to be $\cos\theta = 0.96$. The outer diameter of the central spiral is 12 mm (do_{sp}) and the resulting perimeter (P_{sp}) and cross section (A_{sp}) are 37.699 mm and 113.097 mm^2, respectively.

The outer wrap is overlapped by 45% ($\mathrm{ol}_{ow} = 1.9$) and has a thickness of 0.1 mm (t_{ow}). The subcable wraps cover 80% (cov_{sw}) of the subcable surface and are 0.055 mm thick (t_{sw}) [3]. A correction factor for the subcable wrap cross section is used to account for the rounded edges of the compacted subcable ($\mathrm{cor}_{sw} = 20\ \mathrm{mm}$). The measured average total cross section of subcable and outer wraps is $\mathrm{A}_W = 32.9\ \mathrm{mm}^2$. The

TABLE I
GEOMETRIC PARAMETERS OF THE PFCI SAMPLES

Description	Symbol	Value		Unit	Formula
		Wrap	No Wrap		
Cable space average diameter	d_{cs}	37.53	36.89	mm	(measured)
Cable space area	A_{cs}	1106.234	1068.827	mm^2	$\pi d_{cs}^2/4$
Cable space perimeter	P_{cs}	117.904	115.893	mm	πd_{cs}
Subcable wrap perimeter	P_{sw}	224.101	0.0	mm	$(cov_{sw}(\pi(d_{cs}\text{-}4t_{ow}+do_{sp})+n_{sub}(d_{cs}\text{-}4t_{ow}\text{-}do_{sp})))\text{-}cor_{sw}$
Wrap total cross section	A_W	32.90	0.0	mm^2	(measured)
Outer wrap perimeter	P_{ow}	223.421	0.0	mm	$\pi(d_{cs}\text{-}t_{ow})ol_{ow}$
Twisted strand cross section	A_{st}	627.808	627.808	mm^2	$n_{st}\pi d_{st}^2/4$
Helium in annulus (bundle)	A_B	332.429	327.921	mm^2	$A_{cs}-A_{sp}-A_{st}-A_W$
Void fraction of bundle	v	33.473	34.311	–	$A_B/(A_{cs}-A_{sp})$
Wetted perimeter of bundle	P_w	3222.983	2886.166	mm	$5/6((n_{st}\pi d_{st}/\cos\theta)(1+\cos\theta)/2)+P_{sw}+0.5(P_{sp}+P_{cs}+P_{ow})$
Hydraulic diameter of bundle	d_B	0.413	0.454	mm	$4A_B/P_w$
Sample length	L	1.000	0.631	m	(measured)

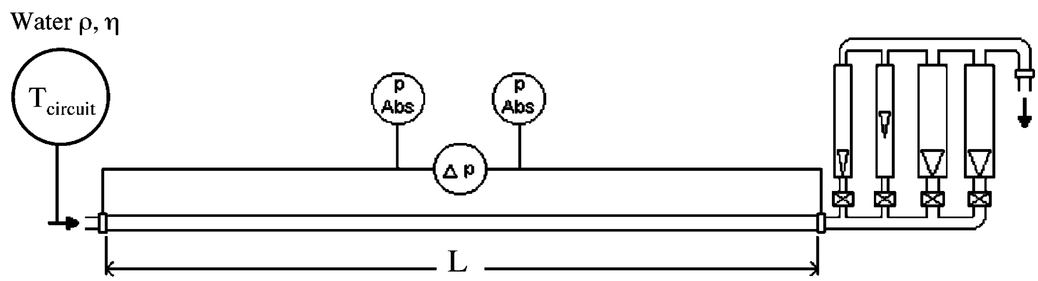

Fig. 2. Schematic view of the experimental set-up, showing the differential and absolute pressure sensors at inlet/outlet, and the floating-ball flow meters. The thermometer is used to derive the average thermodynamic properties of the water. Values of the sample length L are listed in Table I.

measured cable space difference between PFI_W and PFI_{NW} is 37.4 mm^2, i.e. more than the 'missing wraps'. Therefore, since the size of the central channel is identical in both conductors, the helium cross section in the annual space of PFI_{NW} is 4.5 mm^2 smaller than in PFI_W. We assume the contribution to the bundle wetted perimeter (P_W, formula in Table I) of outer wrap, central spiral and cable space perimeter to be one half of the geometrical value.

The central spiral is blocked using a silicon rubber tube, thus restricting the flow to the bundle area. The 10 mm rubber pipe is pulled through the central channel over the whole conductor section and is plugged at the end of the pipe at the outlet side.

B. Experimental Set-Up

The experimental set-up consists of a closed circuit of de-mineralized water at ≈0.8 MPa (Fig. 2). The water temperature in the circuit remains constant during the experiment ($T_{circuit} = T_{inlet} = T_{outlet} = 26°C$ for PFI_W and $= 27°C$ for PFI_{NW}). Therefore, measurements are very accurate since the water density (ρ) and dynamic viscosity (η) are also constant. The sample is horizontal and no correction due to gravity is needed for the pressure drop. The longitudinal friction factor of the annular bundle region is deduced from measurements of pressure drop (Δp) and mass flow rate ($\dot{m}$).

The pressure drop in PFI_W and PFI_{NW} is measured by means of a differential pressure transmitter (signal Δp_d), as well as by two absolute pressure transmitter at inlet and outlet, from which $\Delta p_a = p_{in} - p_{out}$ is derived. The error of the differential and absolute manometers is ±0.2% of the full range, the latter being 0.15 MPa and 3.0 MPa, respectively. The overlap between Δp_a and the more accurate signal Δp_d is in good agreement over a broad range. In the reduction of data the signal Δp_d is retained whenever available (Δp_a is only used for conditions exceeding the full range of the differential pressure transmitter).

The water mass flow rate has been measured by four, parallel operated floating-ball flow meters (Rotameter) having different ranges (100 l/h, 400 l/h, 630 l/h and 1600 l/h, respectively); the error is ±2% of the full scale. The temperature $T_{circuit}$ is measured by a thermometer located in front of the sample inlet, whose accuracy ($\pm 0.5°C$) results in a negligible error bar on the mass flow rate.

III. RESULTS AND DISCUSSION

A. Effect of Wraps

The raw data, i.e. pressure drop per unit length ($\Delta p/L$) versus mass flow rates, show no discontinuity in the full range of the $\dot{m}$ whose upper limit is ≈600 g/s in PFI_W and 800 g/s in PFI_{NW} (Fig. 3). The experimental $\Delta p/L$ is larger in the conductor with wraps (the error bars are small). However, since the two conductors, besides the wrap difference, do not have an exactly identical geometry (Table I), the dimensionless analysis in terms of Reynolds number Re and friction factor f is needed in order to assess their behavior:

$$Re = \frac{(\dot{m} d_B)}{(\eta A_B)} \tag{1}$$

$$f = 2\left(\frac{\Delta p}{L}\right)\rho d_B \frac{A_B^2}{\dot{m}^2} \tag{2}$$

The results of $f(Re)$ are reported in Fig. 4 with the relative error bars $\pm\epsilon_{Re} = |\epsilon_{\dot{m}}|$ and $\pm\epsilon_f = |\epsilon_{\Delta p}| + 2|\epsilon_{\dot{m}}|$, computed using the

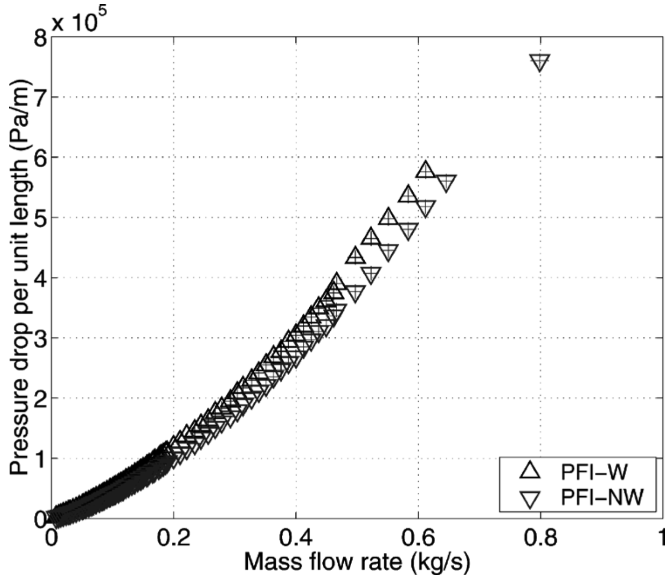

Fig. 3. Results of the raw measurements, including the error bars (inside the symbols).

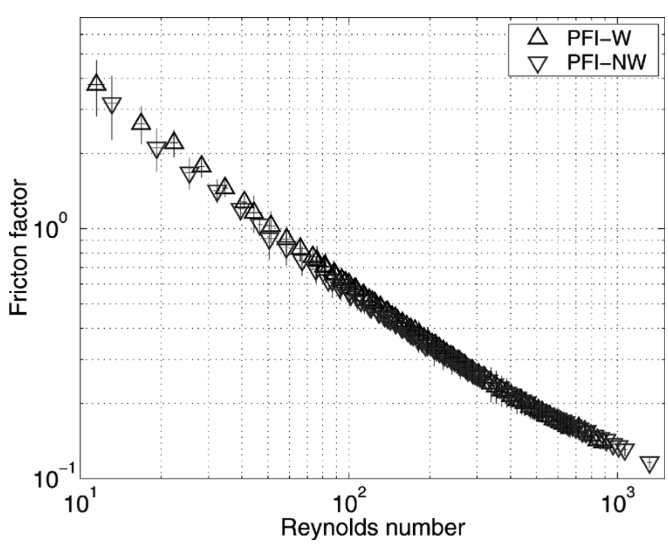

Fig. 4. Results of the dimensionless analysis, including the error bars (see text).

error propagation theory (the errors on the average circuit thermodynamic state are negligible). Within the measurement accuracy, the conductors PFI_W and PFI_{NW} have approximately the same friction factor for $Re > 100$.

The difference between PFI_W and PFI_{NW} is enhanced if $\Delta\mathrm{p/L}$ is plotted as a function of Re instead $\dot{m}$ (Fig. 5). In the same plot are reported the measurements of the ITER Central Solenoid conductor (label CS1), a CICC conductor with wraps (see Table II for bundle wetted perimeter and void fraction) which was tested, with blocked central spiral, in the same experimental set-up [2]. The pressure gradient in the annular bundle region of the wrapped conductors is approximately the same.

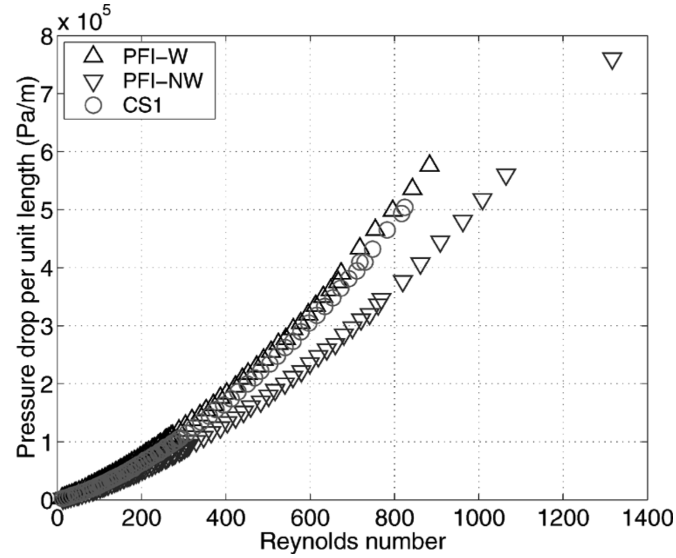

Fig. 5. Pressure drop per unit length as a function of Reynolds number. The results of the ITER CS conductor (with wraps) are also included for comparison with the PFCI conductor with wraps.

TABLE II
COMPARISON OF EXPERIMENTAL RESULTS WITH THE ITER DESIGN CRITERIA CORRELATION

Conductor	v [%]	P_W [mm]	Re	f_{exp}	$f_{ITER-DC}$
PFI_W	33.47	3784.9	717	0.122	0.287
PFI_{NW}	34.31	3448.0	721	0.122	0.281
CS1	36.50	3610.0	721	0.241	0.268

B. Comparison With Correlations

The experimental $f(Re)$ in the annular bundle region has been compared with two correlations for CICC, proposed by Katheder [4] and in the ITER Design Criteria [5]:

$$f_{Katheder} = \left(\frac{1}{v^{0.72}}\right)\left(0.051 + \frac{19.5}{Re^{0.88}}\right) \quad (3)$$

$$f_{ITER-DC} = \left(\frac{1}{v^{0.742}}\right)\left(0.0231 + \frac{19.5}{Re^{0.7953}}\right) \quad (4)$$

Both correlations are only a function of the void fraction v. The Katheder correlation is a fit of measurements of 8 CICC's in the range $20 < Re < 42000$ (best agreement for $1000 < Re < 10000$) and $35\% < v < 47\%$. The range of validity of the ITER Design Criteria correlation is $1000 < Re < 6000$ and $32\% < v < 40\%$. The measured void fractions of PFI_W (33.47%), PFI_{NW} (34.31%) and CS1 (36.50%) are within 3% and, therefore, only one curve of $f_{Katheder}$ (i.e. PFI_{NW}) is plotted in Fig. 6 to avoid unnecessary graphic confusion.

The Katheder correlation overestimates the experimental $f(Re)$ of both PFCI conductors (e.g. +55% at $Re = 820$). An ongoing work on ITER conductor samples (HECOL facility at CEA, Cadarache, France) is qualitatively confirming this result [6]. However, the PFCI result is in disagreement with the CS1 result (shown also in Fig. 6) where $f_{Katheder}$ underestimates the experimental data (e.g. −22% at $Re = 820$). It was argued in [7] that the presence of wrapping could be a possible reason

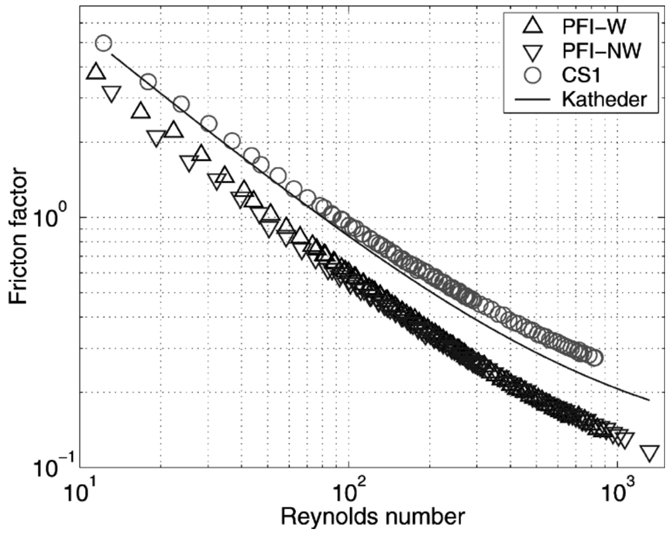

Fig. 6. Comparison of experimental results of the PFCI and CS conductors (open symbols) with the Katheder correlation. For the latter, only the PFI_{NW} curve with $v = 34.31\%$ is shown (see text).

for the disagreement since the Katheder correlation was obtained from samples without wraps, which is not confirmed by the measurements reported here (Fig. 4).

The ITER Design Criteria correlation, which is based on measurements of the ITER CS Model Coil conductor, was derived without the factor 5/6 for the contribution of the strands to the bundle wetted perimeter. Using this wetted perimeter, a punctual example at the upper limit of the Reynolds number for the CS1 measurements is shown in Table II. The experimental PFCI friction factor is more than a factor 2 below $f_{ITER-DC}$, i.e. the disagreement is larger than with respect to the Katheder correlation. This result is outside the range of validity of Re for $f_{ITER-DC}$ and can be extrapolated to higher Re since the measurements are regular.

C. Sensitivity Analysis

There is uncertainty in some geometrical parameters of Table I, due to different reasons. For example, the uncertainty on the bundle wetted perimeter depends of the recipe used to derive it, while the uncertainty on the mean twist pitch angle is due to estimation and comparison of experimental data. The variation of the bundle friction factor of the PFCI conductor is negligible in the range 3037.4 mm (recipe in [7]) $< \mathrm{P}_W < 3223.0$ mm (Table I) and $0.95 < \cos\theta < 0.97$, as shown by a sensitivity analysis.

IV. Summary and Conclusion

The friction factor in the annular bundle region of two PFCI conductors, one with and one without wraps, is assessed in a pressure drop experiment with water in the range of Reynolds number $10 < Re < 1000$. In summary:

- The wraps have a negligible effect on the friction factor.
- The correlation by Katheder overestimates the PFCI experimental friction factor (+55% at $Re = 820$) whereas $f_{Katheder}$ underestimates the friction factor of the CS1 (−22% at $Re = 820$).
- The behavior of the measurements is regular and the extrapolation of the results in the ITER range of interest $(1000 < Re < 6000)$ can be done with confidence.
- The PFCI results are insensitive to two uncertain geometric parameters, i.e. wetted perimeter and mean twist pitch angle.

To date, we cannot explain why the friction factor of the PFCI conductor is considerably smaller than the friction factor of the CS1 conductor. For design purposes, the Katheder correlation can be retained with a ±35% accuracy.

Acknowledgment

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