A CRITICAL ASSESSMENT OF PRESSURE DROP DESIGN CRITERIA FOR THE CONDUCTORS OF THE ITER MAGNETS

R. Zanino[1], P. Bruzzone[2], and L. Savoldi Richard[1]

[1]Dipartimento di Energetica, Politecnico
Torino, 10129, Italy

[2] EPFL - CRPP – Technologie de la Fusion
5232 Villigen-PSI, Switzerland

ABSTRACT

The available database for the friction factors to be used in the annular cable and in the central channel regions of cable-in-conduit conductors (CICC) for the superconducting magnets of the International Thermonuclear Experimental Reactor (ITER) is reviewed here for the first time. There is particular reference to its internal consistency as well as the correlations presently used in the ITER design criteria. Limitations and issues in the present status are emphasized and recommendations for improvements are given.

KEYWORDS: Fusion reactors, ITER, Superconducting magnets, Design criteria, Flows in conduits
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INTRODUCTION

Dual-channel CICC are used for the superconducting magnets of ITER. Supercritical helium in forced convection flows both in the voids of the annular region where the cable bundle is present (a porous structure) and in the lower impedance central channel (hole), delimited by a spiral.

Assessment of the pressure drop along the CICC is crucial in the determination of the pumping cost of the coolant – an important issue in view of the huge hydraulic lengths of several hundred meters present in a coil. This assessment does require suitable correlations for the friction factors [1] in each flow region, i.e., at least one for the bundle region as a

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[1] The Moody definition of the friction factor (4 times the Fanning friction factor) is consistently used everywhere in this paper.

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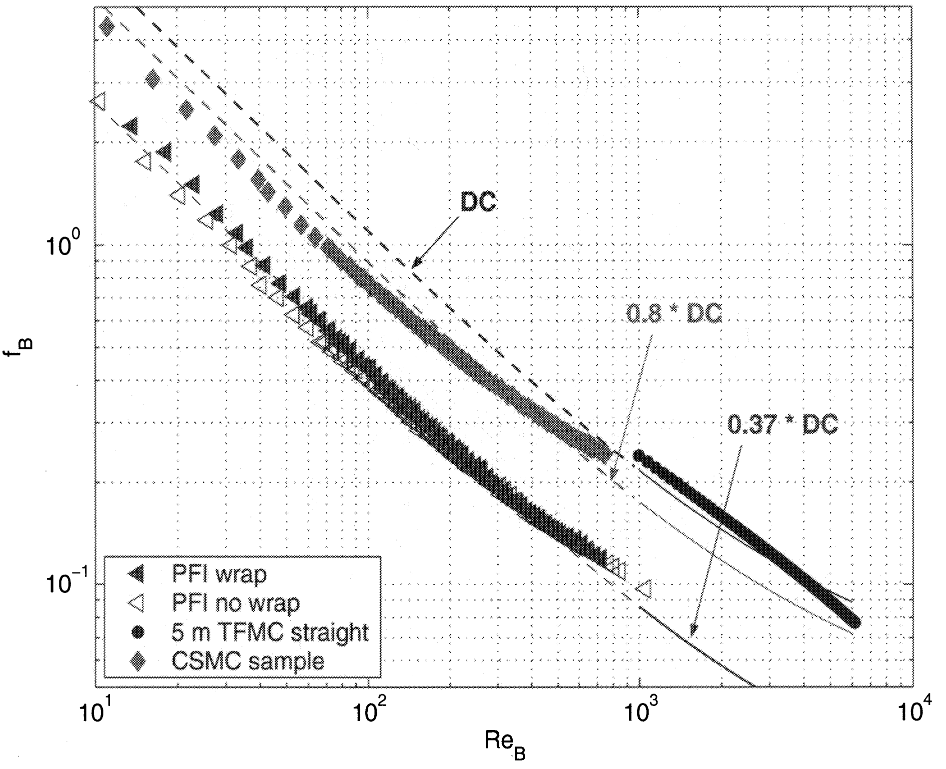

FIGURE 1. Bundle friction factor as a function of the bundle Reynolds number for ITER conductors tested with blocked central channel: PFCI sample with (solid triangles) and without wraps (open triangles), TFMC sample (circles) and CSMC sample (diamonds). Experimental data are reduced without (b) the 5/6 factor in P_{wet} (see text). Friction factors resulting from the DC correlation (1), are also reported, multiplied by a fitting coefficient where relevant. The solid part of the lines represents the original Reynolds range of applicability of (1), while the dashed parts are the extrapolations to lower Re.

whole (f_B) and one for the hole (f_H). These factors also influence the flow repartition in the CICC, i.e., the fraction of flow directly available for cooling of the cable as well as its re-cooling time after transient heating events.

Over the last ten years, several experiments have been performed worldwide on different CICC aimed at providing adequate design criteria (DC) [1] for the pressure drop in this type of conductors. Correlations of the data have been attempted at different levels of complexity.

In this paper, we first consider separately the database and correlations for f_B and f_H and then we assess to what extent the present ITER DC [1] for the two friction factors are able to conservatively predict the pressure drop when compared with the ITER Model Coil (Toroidal Field Model Coil – TFMC – and Central Solenoid Model Coil – CSMC) measurements. A discussion of the issues behind such DC, from a more fundamental point of view, may be found in [2].

TABLE 1. Geometrical data of different ITER-relevant samples vs. ITER coils

Sample/Coil	Void fraction (%)	Spiral ID/OD (mm)	Spiral gap (mm)	Comments
TFMC	36.9	10/12	2.4	5 m sample
CSMC	36.3	10/12	2.7-3.0	5 m sample
PFCI	33.5 – 34.3	10/12	1.7	~ 1 m samples
Showa	-	10/12	2.4	5 m spiral
TF, CS	33.2	7/9	NA	coil
PF	34.2-34.5	10/12	NA	coil

FRICTION IN THE BUNDLE REGION

A correlation for the friction factor f_B in the form used for pebble beds was derived in [3]. The same functional form was adopted in fitting the data from a short (5 m) straight sample of the TFMC conductor resulting in different coefficients [4]. In the present ITER DC:

$$f_B = (1/\phi)^{0.742}(0.0231+19.5/Re_B)^{0.7953} \tag{1}$$

where Re_B is the bundle Reynolds number defined in the ITER DC [2] in terms of a hydraulic diameter $D_h^B = 4\, A_{fluid}^B/P_{wet}$, P_{wet} is the wetted perimeter, ϕ is the void fraction (porosity), defined as A_{fluid}^B/A_{total}^B. The 5/6 factor, traditionally accounting for the non-wetted space inside a strand triplet [5], is adopted in the DC definition of P_{wet}. However, in the derivation of (1) in [4], the 5/6 factor was not used, i.e., there is some contradiction between [4] and the present ITER DC. Here we do adopt (1) with the consistent definition of P_{wet} given in [4].

The available database for f_B of the ITER CICC, including the above-mentioned TFMC sample, is summarized in Fig.1 and compared with the DC, applying suitable multipliers. The database also includes data from a CSMC (CS1.2B) short sample [6] and from two Poloidal Field Conductor Insert (PFCI) short samples [7], one with and the other without last-but-one cabling stage wraps. While the TFMC sample test was performed with N_2, the CSMC and PFCI samples were tested with H_2O, which explains the different Re_B range. All of them where obtained after blocking the central channel with a rubber pipe allowing flow in the annular bundle region only.

Although the CSMC and PFCI data are outside the range of applicability of (1), $1000 < Re_B < 6000$, we attempt to gain some information assuming that the correlation can be extrapolated to lower Re_B. The continuity and monotonicity of the friction factor in the bundle region, down to very low Re_B, was already emphasized in [5]. The only parameter characterizing the CICC that is applied in (1) and the ITER DC is the void fraction. However, while the relative variation of ϕ is at most 10 %, see Table 1, the relative variation of f_B is more than 100 % (when the smaller is taken as reference). This implies that, *for the purpose of analysis/interpretation*, the correlation (1) is generally inadequate to describe the physics of flow in the bundle region and other routes should be considered [2]. However, the ITER DC happen to be derived from the TFMC data, which are those showing the highest pressure drop. Therefore, (1) is conservative based on the presently

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[2] This is not the only possible definition, as other, possibly more physically justified length scales may be identified for a porous medium structure such as the cable bundle, see, e.g., [2].

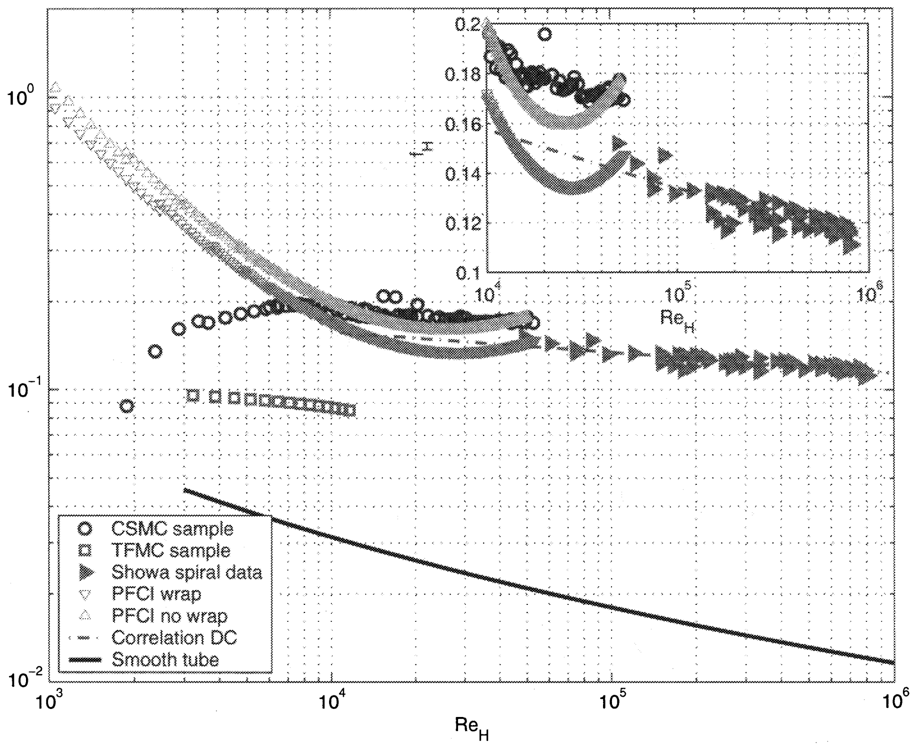

FIGURE 2. Hole friction factor as a function of the hole Reynolds number, measured on different ITER conductor short samples (symbols) and compared with available correlations.

available database and may be considered satisfactory *for the purpose of design* in the range $10 < Re_B < 5\times10^3$.

FRICTION IN THE CENTRAL CHANNEL

In the early ITER DC, a correlation for f_H was given in the form $f_H = \alpha_{fH} \times f^{smooth}$ (Re_H), with $\alpha_{fH} = 2.0$ and Re_H the hole Reynolds number [3]. Later work based on pressure drop vs. mass flow rate data in the QUELL CICC [10] central channel, *under the assumption of validity of [3] for f_B*, verified good agreement using $\alpha_{fH} = 2.5$ [11] (although the definition of D_h^H and A^H was not specified).

However, it soon became apparent that details in the spiral geometry (e.g., its shape – circular vs. flat, or the size *g* of the gap left open between bundle and hole) could have significant influence on the pressure drop, and cannot be condensed in a single multiplier of the smooth pipe friction factor [8], [12]. Tests of spiral rib-roughened pipes using N_2 were performed for three spirals with different gaps in the range 2.4 mm to 5.3 mm with the same ID/OD, including the Showa spiral of Table 1, which *should* be the same spiral as

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[3] There is an important and often overlooked ambiguity in the definition of Re_H, which depends in turn on the definition/choice of both the hole hydraulic diameter, D_h^H, and the hole flow area A^H. In principle, the latter quantities could be defined based on either the inner or the outer hole diameter and, at present, there is little but qualitative reasons to choose between the two [2]. Here we use for both the OD, just in order to be consistent with [8] and [9].

used in both CSMC and TFMC [4]. This database gave rise to least square fits *for each spiral* [8], which have been adopted in the present ITER DC, and furthermore to a general correlation, valid for all three spirals, of the form $f_H = f_H$ (Re_H, g/h) [13], where *h* is the spiral thickness (= 1 mm for all present ITER CICC). For the Showa spiral the ITER DC give

$$f_H = 0.3024\ Re_H^{-0.0707} \tag{2}$$

The present ITER-relevant database is summarized in Fig.2, together with the DC (2) and smooth tube correlations. Except for the Showa spiral data, all other data are obtained from two separate mass flow rate vs. pressure drop measurements. The annular mass flow rate already used above for the determination of f_B is subtracted from the overall mass flow rate, to get the mass flow rate "in the central channel". First of all we may note that the Showa spiral data inexplicably differ from the TFMC short sample by a factor of almost 2, although the spiral in the TFMC sample should be exactly the same as Showa. Second, the CSMC sample data are in reasonable agreement with the extrapolation of the Showa data as expected since the spiral should be the same (however see also the previous note on the uncertainty on *g*). Third, the two PFCI sample data (which do not fall on exactly the same line as they should, since the spiral is the very same, thus giving an indirect indication of the measurement accuracy inside which also the non-monotonicity disappears) agree with both extrapolated Showa and CSMC sample, notwithstanding the fact that a smaller gap would at least qualitatively justify a smaller f_H. These data also show increasing f_H as Re_H decreases below 10^4, as opposed to the CSMC sample.

When comparing measurements and correlations, the ITER spirals appear to give a much stronger increase of friction with respect to the smooth tube, by a factor 6-7 rather than 2.5 [5]. Also the trends disagree, with f_H decreasing with Re_H much less than the smooth tube, as already noted in [13].

From the point of view of the ITER DC, there must be a distinction between the case of the ITER TF and CS coils and that of the PF. The case of the ITER TF and CS falls outside of the presently available database due to the much smaller spiral diameter, see Table 1 [6]. We believe therefore that in this case the issue has to be considered open and can only be settled by dedicated experiments and sophisticated Computational Fluid Dynamics modeling [15]. For the case of the ITER PF, the spiral diameter is foreseen to be conform with that of the presently available database, but information on the rest of the spiral geometry – gap etc. is missing. Nevertheless the present DC are relevant in that case. Notwithstanding all of the above-mentioned inconsistencies and uncertainties, one sees from Fig.2 that the DC are close to giving an acceptable (i.e., conservative) description of the friction factor for all conductors in the present ITER-relevant database. Application of a multiplier (safety factor) of 1.3 in (2) is proposed, which would allow a conservative prediction of all the available data in the range $10^4 < Re_H < 10^6$ (see inset in Fig.2).

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[4] There is some uncertainty as to the quantitative verification of this statement, since measured gaps for TFMC sample, CSMC sample and Showa spiral are actually in the range 2.7 ± 0.3 mm

[5] The needed multiplier would be reduced to ~ 2.5, as in previous literature [11], if hydraulic diameter and flow area were defined in the terms of ID instead of OD

[6] Attempts to extend the present database to different diameters did not include so far the 7/9 ID/OD combination and hit anyway on several issues (smooth tube validation, hydraulic similarity, sensitivity to flow direction) [14], sufficient to make their use rather doubtful in our opinion. Nevertheless, in the ITER DC a correlation for the 7/9 ID/OD case is obtained as average of the correlations derived from 6 mm ID and 8 mm ID data.

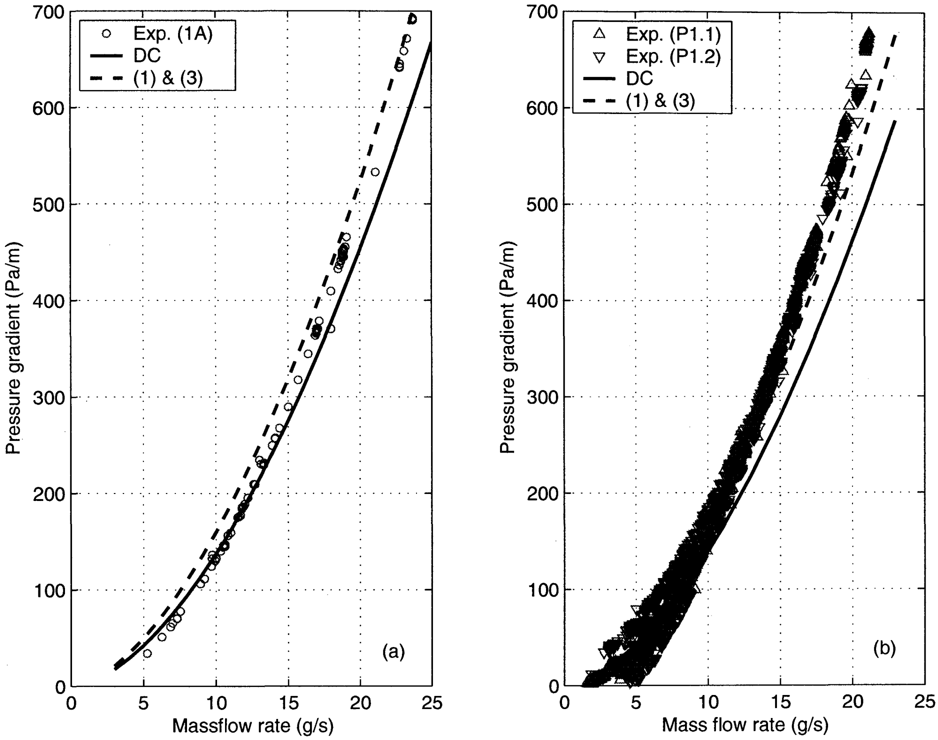

FIGURE 3. Comparison between different predictions and Model Coil data. (a) CSMC; (b) TFMC. The ITER DC (eqs. (1) for f_B and (2) for f_H, solid lines) are compared with the prediction obtained using eqs. (1) for f_B and (3) for f_H, dashed lines.

GLOBAL PRESSURE DROP

We now attempt, as a final step, to verify that the combination of the ITER DC for f_B and f_H, including the proposed corrections, is able to conservatively reproduce the measurements performed on the ITER CSMC conductor 1A [12] and on the ITER TFMC conductors DP1.1 and DP1.2 [16], [9]. These refer to conditions as close as we can get at present to the real ITER coils.

The result of the comparison is shown in Fig.3, where pressure gradient data are reported vs. total mass flow rate. In the case of the CSMC, the DC with multiplier 1-1.3 applied in (2) nicely bracket the experimental data. The comparison is not as satisfactory in the case of the TFMC, where even the most conservative DC estimate falls about 10 % short of the measurements, but can still be considered acceptable. A multiplier of ~ 1.6 in (2) would be needed to make it fully conservative in the whole mass flow rate range of the tests, but this recipe is hardly justified based on the presently available short sample database for f_H (and f_B as well). However, a safety factor of 1.3 is enough for typical 10 g/s ITER mass flow rate, so we propose a modification of the f_H DC as follows

$$f_H = 1.3 \times 0.3024\ \mathrm{Re}_H^{-0.0707} \tag{3}$$

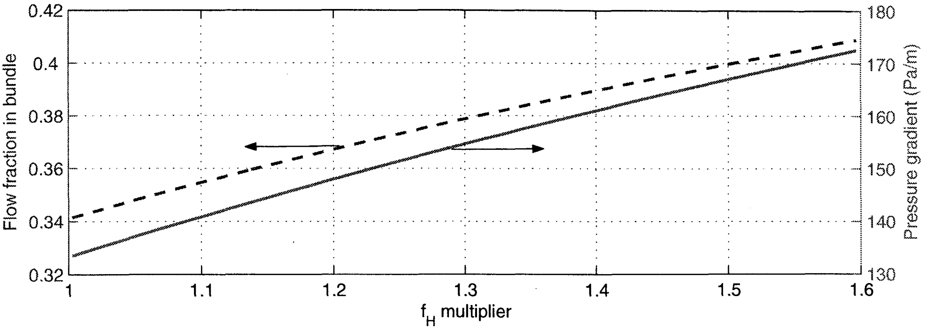

FIGURE 4. Sensitivity of the pressure gradient and of the flow repartition between bundle and hole on the multiplier of (2) at given total mass flow rate (10 g/s He @ 5 K, 5 MPa). TFMC-like conductor data and f_B correlation as in (1) were assumed.

The flow repartition between hole and bundle determined by the use of the multiplier ranging from 1 to 1.6 in (2) is reported in Fig.4. The use of 1.3 as a multiplier leads to an increase of the mass flow rate in the bundle from 34 % to 38%, and the pressure gradient increases from 135 Pa/m to 155 Pa/m.

If the CSMC and TFMC data are compared, we note that the pressure gradient of the TFMC conductor is almost 20 % larger than that of the CSMC. It is difficult to comment on this based on the short sample tests, both because they show different trends for f_B (larger for TFMC) and f_H (larger for CSMC), and because of possible effects of curvature not appearing in the *straight* short sample tests [16], [2].

CONCLUSIONS AND PERSPECTIVE

Although our knowledge of the ITER CICC hydraulics is not satisfactory, the ITER design criteria appear to conservatively reproduce the measured pressure drop in the available database provided a safety factor of 1.3 is applied to the correlation for f_H.

This conclusion applies only to the PF conductors, while for the TF and CS a reliable database for the correlation of f_H at reduced spiral diameter is not yet available.

More work is needed in this direction as well as towards a more fundamental understanding of the ITER CICC hydraulics, aimed at clarifying the role of the different geometrical parameters, both for the annular cable region and for the central channel.

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REFERENCES

1. "ITER Design Description Document. Magnet: Section 1: Engineering description", N 11 DDD 178 04-06-04 R 0.4 (2004).
2. Zanino, R., and Savoldi Richard, L., "A review of thermal-hydraulic issues in ITER cable-in-conduit conductors", submitted to *Cryogenics* for publication (2005).
3. Katheder, H., "Optimum thermohydraulic operation regime for cable-in-conduit superconductors", *Cryogenics* **34** ICEC Supplement, pp. 595-598 (1994); Katheder, H., "A general formula for calculation of the friction factor for cable in conduit conductors", NET Report N/R/0821/26/A (1993).

4. Nicollet, S., Cloez, H., Duchateau, J.L., and Serries, J.P., “Hydraulics of the ITER Toroidal Field Model Coil Cable-In-Conduit Conductors”, *Proceedings* of the 20th Symposium on Fusion Technology 1998, pp. 715-718.
5. Lue, J.W., Miller, J.R., and Lottin, J.C., “Pressure drop measurement on forced flow cable conductors”, *IEEE Trans. Mag.* **15**, pp. 53-55 (1979).
6. Bruzzone, P., “Pressure drop and helium inlet in the ITER CS1 conductor”, *Fus. Eng. Des.* **58-59**, pp. 211-215 (2001)
7. Marinucci, C., Bruzzone, P., della Corte, A., Savoldi Richard, L. and Zanino, R., “Pressure drop of the ITER PFI cable-in-conduit conductor”, *IEEE Trans. Appl. Supercond.* **15**, pp. 1383-1386 (2005).
8. Nicollet, S., Duchateau, J.L., Fillunger, H., Martinez, A., and Parodi, S., “Dual Channel cable in conduit thermohydraulics: influence of some design parameters”, *IEEE Trans. Appl. Supercond.* **10,** pp. 1102-1105 (2000).
9. Nicollet, S., Duchateau, J.L., Fillunger, H., Heller, R., Maix, R., Savoldi, L., Zahn, G., and Zanino, R., "Hydraulic resistance of the ITER TFMC dual channel CICC pancakes", in *Proceedings* of the 19th International Cryogenic Engineering Conference, 2002, pp. 161-164.
10. Anghel, A., Blau, B., Fuchs, A.M., Heer, B., Marinucci, C., Vecsey, G., Takahashi, Y., Hamada, K., Fujisaki, H., Smith, S., Pourrahimi, S., Shaji, A., Schultz, J. H., Zhelamskij, M., Klimchenko, A. and Lancetov, A., The quench experiment on long length (QUELL), Final report, Villigen, Naka, Cambridge, St. Petersburg 1997.
11. Hamada, K., Takahashi, Y., Koizumi, N., Tsuji, H., Anghel, A., Blau, B., Fuchs, A., Her, B., Vecsey, G., Smith, S., Purrahimi, S. and Zhelamskij, M., “Thermal and hydraulic measurement in the ITER QUELL experiments”, in *Adv. Cryo. Eng.* 43 , edited by P. Kittel, Plenum, New York, 1998, pp. 97-204.
12. Hamada, K., Kato, T., Kawano, K., Hara, E., Ando, T., Tsuji, H., Okuno, K., Zanino, R., and Savoldi, L., “Experimental results of pressure drop measurement in ITER CS Model Coil tests”, in *Adv. Cryo. Eng.* 47, edited by S. Breon et al., New York, 2002, pp. 407-414.
13. Zanino, R., Santagati, P., Savoldi, L., Martinez, A., and Nicollet, S., "Friction factor correlation with application to the central cooling channel of cable-in-conduit super-conductors for fusion magnets", *IEEE Trans. Appl. Supercond.* **10,** pp. 1066-1069 (2000).
14. Zanino, R., and Savoldi Richard, L., “Task TW1-TMC CODES Design and interpretation codes. Del. 1a. Part 1: Investigation on flow characteristics (Analysis of pressure drop tests in OTHELLO)”, April 2005 (unpublished).
15. Zanino, R., Giors, S., and Mondino, R., “CFD modeling of ITER cable-in-conduit super-conductors. Part I: Friction in the central channel”, presented as paper C2-L-03 at the 2005 Cryogenic Engineering Conference, Keystone (CO) USA, accepted for publication in *Adv. Cryo. Eng.* (2006).
16. Zanino, R., Bagnasco, M., Fillunger, H., Heller, R., Savoldi Richard, L., Suesser, M., and Zahn, G., “Thermal-hydraulic issues in the ITER Toroidal Field Model Coil (TFMC) test and analysis”, in *Adv. Cryo. Eng.* 49**,** edited by J. Waynert, New York, 2004, pp. 685-692.