Fusion Engineering and Design 124 (2017) 1191–1194

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Experimental stand for thermal-hydraulic tests of forced flow conductors using water at room temperature

Monika Lewandowska [a,*], Wojciech Rachtan [a], Aleksandra Dembkowska [a], Leszek Malinowski [a], Louis Zani [b]

[a] West Pomeranian University of Technology, Szczecin, 70-310 Szczecin, Poland
[b] CEA, IRFM, F-13108 St-Paul-lez-Durance, France

HIGHLIGHTS

- New installation THETIS for hydraulic tests of superconducting cables is presented.
- Pressure drop tests are performed using water at room temperature.
- First test results of the reference sample (JT-60SA TF conductor) are reported.
- Extension of THETIS capabilities to enable thermal-hydraulic tests is foreseen.

ARTICLE INFO

Article history:
Received 2 October 2016
Received in revised form 20 April 2017
Accepted 9 May 2017
Available online 24 May 2017

Keywords:
Pressure drop
Friction factor
Superconducting cables

ABSTRACT

A new installation (THETIS) for thermal-hydraulic tests of forced-flow superconducting cables used in fusion technology, such as e.g. Cable-in-Conduit Conductors (CICCs), has been prepared at West Pomeranian University of Technology, Szczecin. The installation enables pressure drop measurements using water at room temperature in short samples of conductors in a wide range of Reynolds number. We present the new installation and demonstrate its capabilities by reporting the results of the first hydraulic test conducted on a reference sample (JT-60SA TF conductor). Further development of THETIS is foreseen to make possible measurements of heat transfer coefficients in superconducting cables.

1. Introduction

Current models used for thermal–hydraulic analyses of forced-flow superconducting cables used in fusion technology are typically 1-D and they require reliable predictive correlations for the transverse mass-, momentum- and energy transport processes occurring between different cable components, in order to assess any fusion magnet design in both normal and off-normal operating conditions [1]. The void fraction of some Nb_3Sn superconducting cables designed for the DEMO Toroidal Field coil is strongly reduced (down to about 20%) [2]. Conductors with such low void fractions have never been tested for pressure drop yet. Moreover, it was observed [2], that discrepancies between predictions of different bundle friction factor correlations available in literature [3–5] strongly increase with decreasing the void fraction. There is a need of experimental verification of the accuracy of the existing predictive friction factor correlations at very low void fractions. The situation with heat transfer phenomena in a CICC bundle is even less satisfactory. Only a few heat transfer correlations for flow in a CICC bundle have been proposed in literature [6–8], but none of them is widely accepted for predictive purposes. As a result, in thermal-hydraulic analyses of conductors designed for the DEMO coils [1,9–13] classical heat transfer correlations for flows in smooth tubes are used, which are definitely over-conservative in this case. Systematic measurements of heat transfer coefficients in a CICC bundle should be performed which could serve as a base for further attempts to develop a predictive correlation.

To reliably assess the predictive capability of an existing bundle friction factor correlation, or to develop a new one, it is beneficial to have experimental data measured in a possibly wide range of Reynolds number (Re). Friction factor data can be derived from pressure drop measurements using different fluids, e.g. water [14–18] or nitrogen [19,20] at room temperature (RT), or helium at room or cryogenic temperatures [5,17,18,21–23]. The largest Re range can be reached when the same sample is tested with water and another, less viscous, fluid [17,18], however, it would be desir-

---

[*] Corresponding author.
E-mail address: monika.lewandowska@zut.edu.pl (M. Lewandowska).

http://dx.doi.org/10.1016/j.fusengdes.2017.05.047

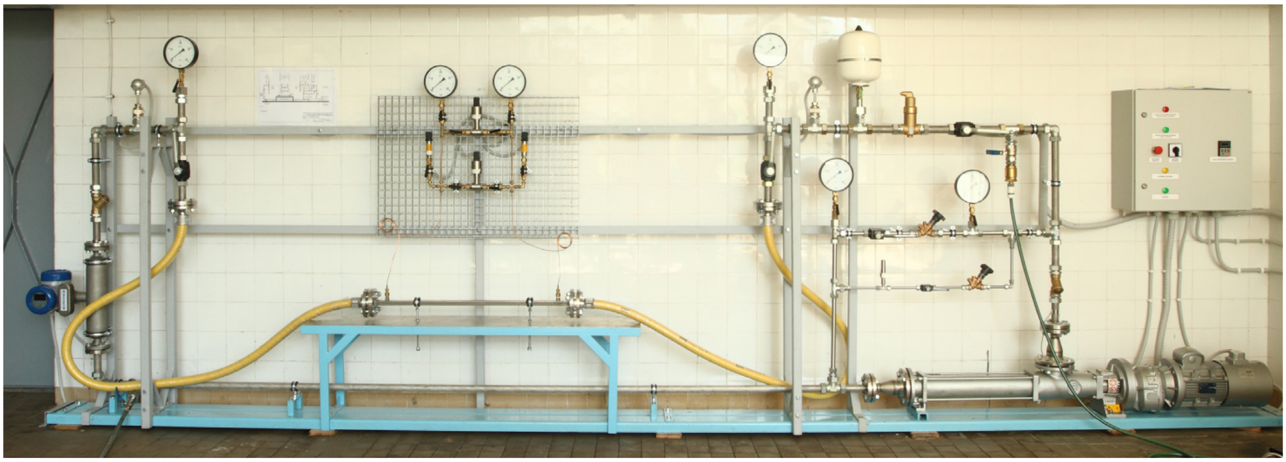

Fig. 1. Photo of the THETIS installation.

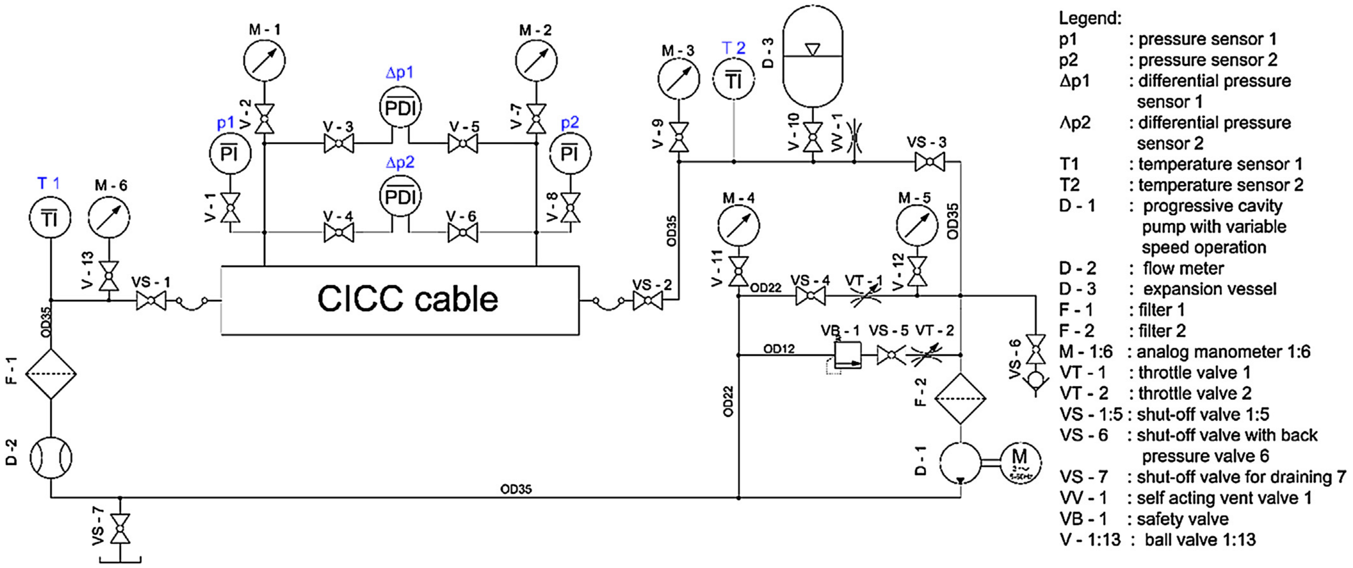

Fig. 2. Hydraulic scheme of the installation.

able to have experimental data covering the whole considered Re range. Systematic experimental studies of pressure drop in CICCs with different void fractions and cable layouts, using water at RT, were conducted in EPFL-CRPP [14–18], however in these experiments the maximum pressure at the sample inlet was 1 MPa, which limited the maximum Re which could have been reached, particularly for conductors with low void fractions.

A new installation (THETIS) for thermal-hydraulic tests of forced-flow superconducting cables used in fusion technology, such as e.g. CICCs, is being prepared at West Pomeranian University of Technology, Szczecin. The first stage of its construction has been completed. The aim of the paper is to present THETIS and demonstrate its capabilities by reporting the results of the first performed hydraulic test.

2. Experimental setup

2.1. THETIS installation

At the present stage the THETIS installation enables pressure drop tests of short conductor samples using distilled water at room temperature. The photo of the installation and its hydraulic scheme is presented in Figs. 1 and 2. The pressure head up to 2.5 MPa in the installation is induced by a progressive cavity pump (BELLIN LZ 500L/KW) with variable speed operation. This allows to reach the pressure drop along the test section of a cable up to about 1.9 MPa. The mass flow rate in the circuit is adjusted by changing the rotational speed of the pump in the range 10–60 Hz. Two bypasses of the pump with different diameters enable precise adjustment of small mass flow rates by suitable opening of two throttle valves (VT-1 and VT-2 in Fig. 2). The minimum mass flow rate which can be measured in THETIS is of about 5.5 g/s. The tolerable range of the water temperature in the installation is 10–70 °C. A conductor sample is attached to the installation using flexible hoses with flange connections, which allows to vary the sample length in the range of about 0.5–2 m. The applied measuring instrumentation (see Table 1) and the automatic data acquisition system enable accurate and convenient measurements.

2.2. Reference sample

A reference sample used for the first pressure drop test performed with THETIS was the JT60-SA TF single channel CICC (JTF091). Full characteristics of this conductor is given in [20,24], whereas the conductor parameters relevant for the present study are recalled in Table 2.

Table 1
Specification of the instrumentation used in THETIS.

Measuring instrument	Type	Measured quantity	Measuring range	Basic measurement uncertainty
Flow meter	KROHNE OPTIMASS 1000	$\dot{m}$	20–3000 kg/h	±0.15% of measured value
Temperature sensor 1 and 2	T-111-6-115-60-3-G1/2-NA-A-Pt1000-400	T_1, T_2	−200–400 °C	±0.15 °C ±0.2% of |measured value|
Pressure sensor 1	Aplisens PR-28/0-25BAR/M20 × 1.5	p_1	0–2.5 MPa	±0.2% of measuring range
Pressure sensor 2	Aplisens PR-28/0-10BAR/M20 × 1.5	p_2	0–1 MPa	±0.2% of measuring range
Differential pressure sensor 1	Aplisens APR-2000PD/0-250KPA/P/M20 × 1.5	Δp_1	0–0.25 MPa	±0.1% of measuring range
Differential pressure sensor 2	Aplisens APR-2000PD/0-16 bar/P/M20 × 1.5	Δp_2	0–1.6 MPa	±0.1% of measuring range
Data Acquisition System	APAR AR207	–	–	±0.1% of measuring range

Table 2
Characteristics of the JTF091 sample [20].

Description	Symbol	Unit	Value
Void fraction	φ	%	32
Flow area	A_f	mm^2	125.8
Hydraulic diameter	D_h	mm	0.454
Distance between pressure taps	L	m	0.865

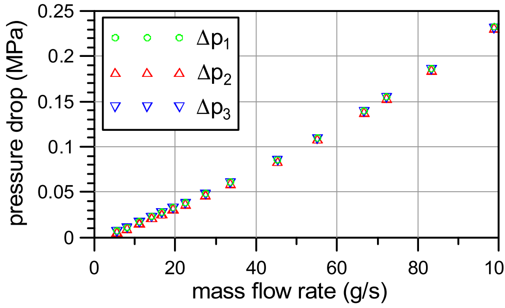

Fig. 3. Comparison of the values of pressure drop measured using different pressure sensors. Typical values of uncertainties are: $u(\Delta p_1) = 0.00036$ MPa, $u(\Delta p_2) = 0.0023$ MPa and $u(\Delta p_3) = 0.0061$ MPa.

3. Test results and discussion

The mass flow rate in the circuit was increased stepwise and readings of the sensors listed in Table 1 were registered in 1 s intervals. The average values and their standard deviations were calculated for the data collected during steady states. To assess pressure drop in the sample, readings of the pressure sensors p_1 and p_2 were used in the range $\Delta p_3 = p_1 - p_2 > 1.6$ MPa, whereas the more accurate differential pressure sensors Δp_2 and Δp_1 were used in the range 0.25 MPa < Δp_2 < 1.6 MPa, and Δp_1 below 0.25 MPa, respectively. The overlap between Δp values measured with different sensors was in good agreement within the range of uncertainties and confirmed the good accuracy of their calibration (Fig. 3).

The longitudinal Darcy friction factor (f) and the Reynolds number were deduced from measurements of pressure drop and mass flow rate ($\dot{m}$), according to the formulas:

$$f = \left(2D_h \rho A_f^2 \Delta p\right) / \left(\dot{m}^2 L\right), \quad (1)$$

$$Re = \left(\dot{m} D_h\right) / \left(\mu A_f\right), \quad (2)$$

where the water density (ρ) and dynamic viscosity (μ) were calculated at the reference conditions: $p_{ref} = p_{ambient} + (p_1 + p_2)/2$ and $T_{ref} = (T_1 + T_2)/2$. The uncertainties of the friction factor and Re were calculated as [25]:

$$u(f) = f\sqrt{\left(\frac{u(\Delta p)}{\Delta p}\right)^2 + 2\left(\frac{u(\dot{m})}{\dot{m}}\right)^2 + \left(\frac{u(L)}{L}\right)^2}, \quad (3)$$

$$u(Re) = \left(u(\dot{m}) D_h\right) / \left(\mu A_f\right). \quad (4)$$

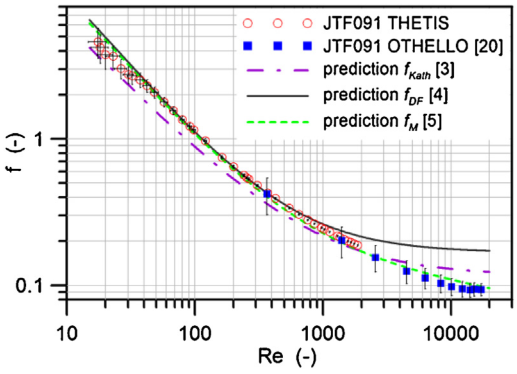

Fig. 4. Comparison of our test results with the results of pressure drop test of the same sample performed at the OTHELLO test facility and with predictions of the friction factor correlations taken from literature [3–5].

The results of the performed test in the dimensionless form (f vs. Re) are presented in Fig. 4. Over seventy JT-60SA TF short samples, cut from different conductor unit lengths provided by manufactures, were tested for pressure drop in the OTHELLO test facility using nitrogen at RT [20]. Although the design of all these conductors was identical a noticeable scattering of the pressure drop test results was reported in [20]. The test results of the JTF091 sample obtained in this experimental campaign have been added in Fig. 4. For the sake of comparison we have also included in Fig. 4 predictions of different friction factor correlations taken from literature [3–5]. It is seen in Fig. 4 that our test results agree very well with the results of the test of the same sample performed at the OTHELLO test facility [20], and are consistent with predictions of friction factor correlations [3–5] used in thermal-hydraulic analyses of the DEMO TF coils [1,9–12]. The Re range achievable at THETIS and OTHELLO partially overlap. Both installations can be considered as complementary, and allow together to achieve a very wide Re range necessary for reliable experimental verification of the existing friction factor correlations for conductors with very low void fraction.

4. Summary, conclusions and perspectives

The new THETIS installation for thermal-hydraulic tests of forced flow cooled superconducting cables using water at RT is being prepared at the West Pomeranian University of Technology, Szczecin. At the present stage THETIS enables convenient and accurate pressure drop tests of short conductor samples. The performed pressure drop test of the reference sample (JT-60SA TF CICC) demonstrated that the Re range achievable in THETIS is complementary to that of the OTHELLO test facility. Further development of THETIS is foreseen, e.g. adding several temperature sensors as well as a heater at the sample inlet and a cooler at the sample outlet, to make possible measurements of hydraulic resistance and heat transfer coefficients in superconducting cables in different temperatures. External teams are invited to send us conductor samples to be tested, on a collaborative basis.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This scientific work was also partly supported by Polish Ministry of Science and Higher Education within the framework of the scientific financial resources in the year 2016 allocated for the realization of the international co-financed project.

We are indebted to Mr. B. Białecki for technical support.

References

[1] R. Zanino, L. Savoldi Richard, A review of thermal-hydraulic issues in ITER cable-in-conduit conductors, Cryogenics 46 (2006) 541–545.
[2] M. Lewandowska, K. Sedlak, L. Zani, Thermal-hydraulic analysis of the low-Tc superconductor (LTS) winding pack design concepts for the DEMO toroidal field (TF) coil, IEEE Trans. Appl. Supercond. 26 (2016) 4205305.
[3] H. Katheder, Optimum thermohydraulic operation regime for cable in conduit superconductors (CICS), Cryogenics 34 (1994) 595–598.
[4] M. Bagnasco, L. Bottura, M. Lewandowska, Friction factor correlation for CICCs based on a porous media analogy, Cryogenics 50 (2010) 711–719.
[5] M. Lewandowska, M. Bagnasco, Modified friction factor correlation for CICC's based on a porous media analogy, Cryogenics 51 (2011) 541–545.
[6] S. Nicollet, D. Ciazynski, J.-L. Duchateau, B. Lacroix, B. Renard, Evaluation of the ITER cable-in-conduit-conductor heat transfer, in: Proceedings of the 20th ICEC, Elsevier Ltd., Beijing, China, 2005, pp. 589–592.
[7] L. Bottura, C. Marinucci, A porous medium analogy for the helium flow in CICC's, Int. J. Heat Mass Transf. 51 (2008) 2494–2505.
[8] M. Lewandowska, L. Malinowski, Transverse heat transfer coefficient in the dual channel ITER TF CICCs. Part III: direct method of assessment, Cryogenics 73 (2016) 91–100.
[9] M. Lewandowska, K. Sedlak, Thermal-hydraulic analysis of LTS cables for the DEMO TF coil, IEEE Trans. Appl. Supercond. 24 (2014) 4200305.
[10] M. Lewandowska, K. Sedlak, Thermal-hydraulic analysis of the improved LTS conductor design concepts for the DEMO TF coil, Prz. Elektrotech. 92 (2016) 179–182.
[11] R. Zanino, et al., Development of a thermal-hydraulic model for the European DEMO TF coil, IEEE Trans. Appl. Supercond. 26 (2016) 4201606.
[12] R. Vallcorba, et al., Thermo-hydraulic analyses associated with a CEA design proposal for a DEMO TF conductor, Cryogenics 80 (December) (2016) 317–324.
[13] R. Zanino, L. Savoldi, Common Approach for Thermal-Hydraulic Calculations, Memo for WPMAG-MCD-2.1, IDM Reference: EFDA_D_2LMECE, 2016.
[14] P. Bruzzone, Pressure drop and helium inlet in the ITER CS1 conductor, Fusion Eng. Des. 58–59 (2001) 211–215.
[15] C. Marinucci, P. Bruzzone, A. della Corte, L. Savoldi Richard, R. Zanino, Pressure drop of the ITER PFI cable-in-conduit conductor, IEEE Trans. Appl. Supercond. 15 (2005) 1383–1386.
[16] M. Bagnasco, et al., Pressure drop of cable-in-conduit conductors with different void fraction, Adv. Cryog. Eng. 53 (2008) 1317–1324.
[17] M. Bagnasco, M. Lewandowska, Pressure drop measurements in cable-in-conduit conductors (CICC) with different layouts, in: Proceedings of the 22nd ICEC-ICMC, Seoul, 2008, pp. 865–870.
[18] M. Lewandowska, M. Bagnasco, Pressure drop measurements in cable-in-conduit conductors (CICC's) for an extended range of Reynolds number, Prz. Elekrotech. 85 (2009) 155–157.
[19] S. Nicollet, H. Cloez, J.L. Duchateau, J.P. Serries, Hydraulics of the ITER toroidal field coil cable-in-conduit conductors, Proceedings of the 20th SOFT (1998) 771–774.
[20] P. Decool, et al., JT-60SA TF coils: experimental check of hydraulic operating conditions, IEEE Trans. Appl. Supercond. 26 (2016) 4201705.
[21] J.W. Lue, J.R. Miller, J.C. Lottin, Pressure drop measurement on forced flow cable conductors, IEEE Trans. Magn. 15 (1979) 53–55.
[22] M.A. Daugherty, Y. Huang, S.W. Van Sciver, Pressure drop measurements on supercritical helium cooled cable in conduit conductors, IEEE Trans. Magn. 25 (1989) 1512–1515.
[23] M.A. Daugherty, S.W. Van Sciver, Pressure drop measurements on cable-in-conduit conductors of various geometries, IEEE Trans. Magn. 27 (1991) 2108–2111.
[24] L. Zani, P. Barabaschi, M. Peyrot, Starting EU production of strand and conductor for JT-60SA toroidal field coils, IEEE Trans. Appl. Supercond. 22 (2012) 4801804.
[25] B.N. Taylor, C.E. Kuyatt, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results. NIST Technical Note 1297, 1994.