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Low friction cryostat for HTS power cable of Dutch project

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Abstract

Particulars of 6 km long HTS AC power cable for Amsterdam project are: a cable has to fit in an annulus of 160 mm, with only two cooling stations at the cable ends [1]. Application of existing solutions for HTS cables would result in excessively high coolant pressure drop in the cable, possibly affecting public acceptance of the project. In order to solve this problem, a model cryostat was developed consisting of alternating rigid and flexible sections and hydraulic tests were conducted using sub-cooled liquid nitrogen. In the 47 m-long cryostat, containing a full-size HTS cable model, measured pressure drop amounts 11 mbar at the mass flow rate of 0.3 kg/s and temperature 65 K. For a 6 km-long HTS cable this gives a pressure drop below 2 bar, which is acceptable. In order to achieve this result, the cryostat was manufactured from alternating straight rigid sections and corrugated flexible sections. A flexible dummy HTS cable was inserted into this cryostat and sub-cooled liquid nitrogen was circulated in the annulus between the dummy cable surface and the inner cryostat surface. In the paper details are presented of the cryostat, of the measurement setup, of the experiment and of the results.

Keywords: long HTS AC power cable, Dutch project, model cryostat, alternating rigid and flexible sections, hydraulic measurements, low friction, Reynolds number, friction factor

1. Introduction

For successful making long HTS cables using corrugated pipes, low pressure drop and low friction factor are essential. The friction factor depends on the Reynolds number, corrugation height and pitch and other conditions [2]. In this paper we measure experimentally the pressure drop and the friction factor for the 47 m long cryostat containing a model HTS cable.

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Nomenclature

f	friction factor
ρ	fluid density
μ	fluid dynamic viscosity
L	tube length
F_c	cross-sectional area of the flow
G	mass flow rate
w	fluid velocity defined as $G/(\rho F_c)$
P_w	wetted perimeter of the flow
D_h	hydraulic diameter of the tube defined as $4F_c/P_w$
Re	Reynolds number defined as $\rho w D_h/\mu$
Δp	pressure drop along the tube

The total pressure drop in a cable is:

$$\Delta p = f\rho w^2 L/(2D_h) \tag{1}$$

For classical straight pipes with a certain wall roughness the friction factor can be extracted from the Moody's chart [2]. HTS cables usually have more complex geometry and a better estimate of the friction factor can be achieved using [3-5].

2. The sample

Schematic representation of the hydraulic circuit for testing the cryostat is given in Fig. 1. The 46.5 m long cryostat consists of three straight sections and two flexible sections made of corrugated tubes.

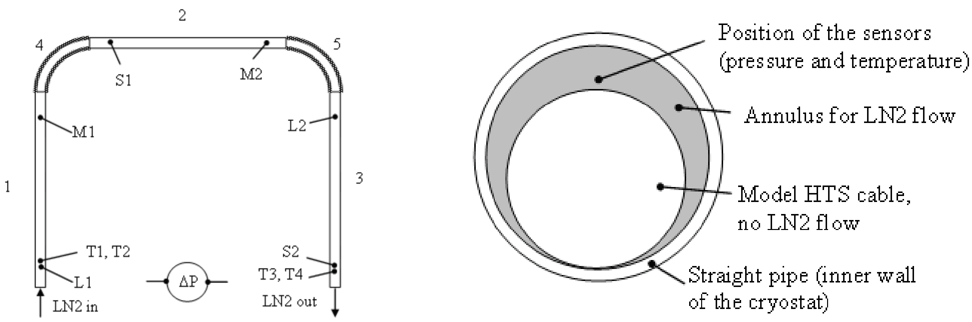


Figure 1 Left: schematic representation of hydraulic circuit for testing the cryostat: 1, 2 and 3 are the three straight sections (each 12.5 m long); 4 and 5 are the two flexible sections, (each 4.5 m-long); labels of the points are also shown where the capillary tubes probe the flow of liquid nitrogen (L1, M1, S1, M2, L2 and S2) and where the temperatures are measured: T1, T2 (inlet of the cryostat) and T3, T4 (outlet of the cryostat). Right: the precision differential pressure meter can be connected to any of the capillary tubes via a manifold (not shown in the figure). Hydraulic cross-sectional view of the model cryostat (straight sections).

A dummy cable was inserted freely into the cryostat and liquid nitrogen was circulated in the annulus between the dummy cable surface, and the inner cryostat surface, Fig. 1, right. Each straight section was 12.5 m long, with 0.103 m inner diameter and roughness 0.1 mm; each corrugated section was 4.5 m long, with 0.103 m inner diameter, with the corrugation depth and pitch of 3 mm and 3 mm respectively. Outer diameter of the dummy cable was 0.081 m and its length was equal to that of the cryostat. Calculated hydraulic diameters for the straight and the corrugated sections are 0.022 m and 0.015 m respectively. The inner diameter of straight and corrugated sections is kept the same allowing thicker thermal insulation in the bendable sections of the cryostat. As clear from Fig. 1, left, for practical reasons both corrugated sections were 90 degrees bent (in order to shorten a distance between the cryostat ends, see also Fig. 2).

3. Measurement setup

An image of the complete setup for hydraulic test of the cryostat is given in Fig. 2. The setup consists of the cryostat, with the insert representing HTS cable model, the cooling machine, the vacuum pumps, the connecting tubes, the capillary pipes, wires, cables, measurement instruments and acquisition system.

Four precision thermometers PT100 were mounted in the nitrogen flow inside the cryostat (points T1, T2 T3 and T4, see Fig 1 and connected to the multi-channel temperature measurement system МИТ 8.15. Six capillary tube probes were mounted in the flow (points L1, M1, S1, M2, L2 and S2, Fig. 1) to measure the pressure drop along the cryostat. The absolute pressure and the flow rate were measured at the flow entrance (outside the cryostat by the cooling machine, see Figs. 1, 2). The capillary pipes probing the flow pressure were placed inside the dummy cable, taken out at the cryostat ends and connected to the manifold at room temperature. Using the manifold, any two capillary pipes could be connected to the differential pressure meter.

4. Measurement results

The friction factor was calculated from the measured pressure drop, the mass flow rate, the temperature, the pressure, assuming D_h=0.015 m and using Eq. (1), see Fig. 3. The dots are the measured points, and the line is the linear fit with Equation (2):

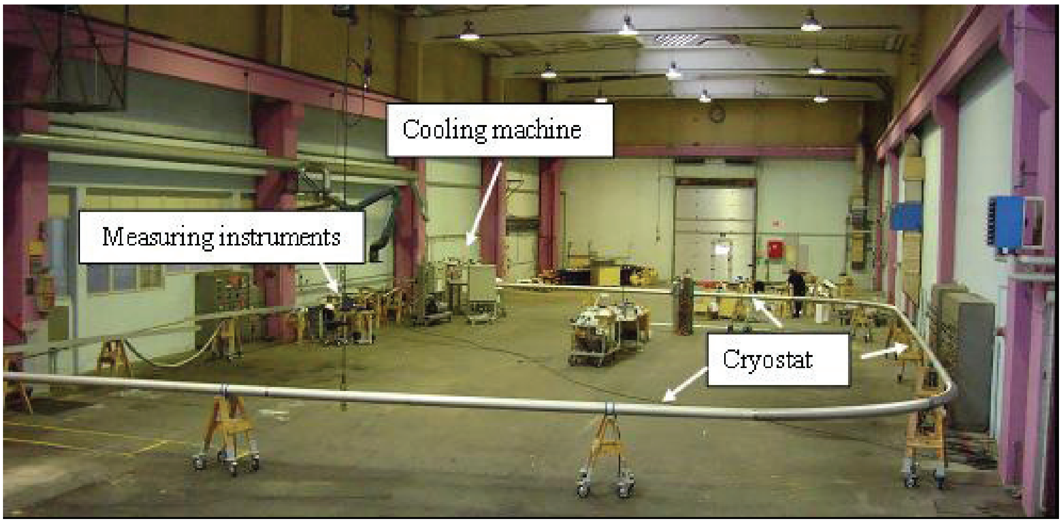
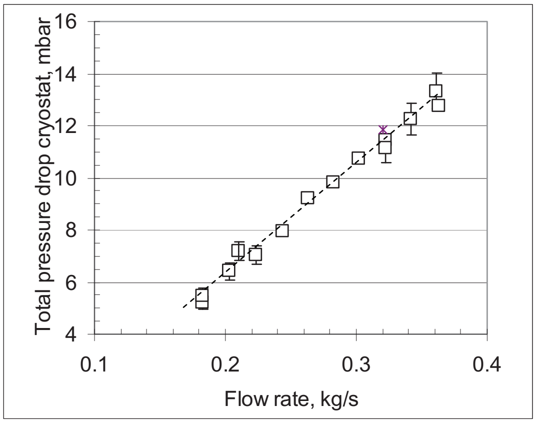


Figure 2 Complete setup for the hydraulic test of 47 m-long cryostat

$$f = 0.1192 - 5.616 \cdot 10^{-6}\,\mathrm{Re}\,. \tag{2}$$

The two main results are depicted in Fig. 3: the pressure drop increases linearly with the flow rate (in the range from 0.18 to 0.36 kg/s) and the measured friction coefficient descends between 0.095 and 0.05 linearly with the Reynolds number increasing (from 4500 to 11500). Similar descending dependence was measured in [5].



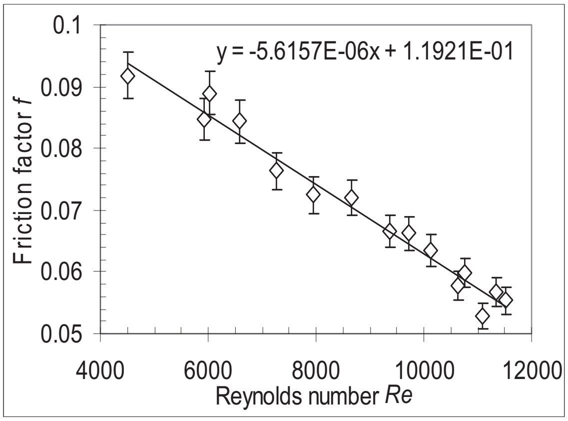


Figure 3 Left: measured dependence of the total pressure drop across the cryostat length versus the mass flow rate (the temperature and the pressure were varied from 68 to 82 K and from 0.8 bar to 1.5 bar); right: friction factor of the cryostat versus the *Re* number.

It is clear from Fig. 3, left that the measured total pressure drop along the cryostat is 11 mbar at the mass flow rate of 0.3 kg/s and when extrapolated to 0.4 kg/s, gives 15 mbar. For the cryostat of the same dimensions made entirely with corrugated pipes, the friction factor of 0.1 and the pressure drops of 20 mbar and 40 mbar respectively are expected at the same flow rates of 0.3 and 0.4 kg/s [4].

5. Conclusion

In the practical range of mass flow rate, temperature and pressure of the sub-cooled liquid nitrogen, we have demonstrated experimentally a substantial reduction of the pressure drop inside the 47 m long cryostat made of alternating rigid and flexible sections and containing a full-size HTS cable model. Extrapolation of the main result for a 6 km-long HTS cable of Amsterdam project gives a pressure drop below 2 bar (0.3 kg/s and 68 K), which is acceptable figure.

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