Long-Term Monitoring of Hydraulic Characteristics of LHD Poloidal Coils[*)]

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(Received 30 November 2011 / Accepted 24 January 2012)

We present a fourteen-year data summary of the hydraulic characteristics of the large helical device (LHD) poloidal coils. The superconductors of the poloidal coils are cable-in-conduit conductors (CICC) cooled by circulated supercritical helium. The long-term operation of the LHD demonstrates that the initial hydraulic characteristics can be maintained without flow obstruction. Fine mesh filters installed at the inlet trapped impurities during cool-down of the coils, confirmed by monitoring the pressure drop of the filters. The filters have an important role in removing particles of impurities in the helium and maintaining the hydraulic characteristics of the coils.

Keywords: LHD, superconducting magnet, cable-in-conduit conductor, hydraulic characteristic, friction factor

DOI: 10.1585/pfr.7.2405008

1. Introduction

The Large Helical Device (LHD) is a fully superconducting experimental fusion apparatus [1]. The superconducting magnetic system consists of two types of superconducting coils, pool-cooled helical coils and forced-flow-cooled poloidal coils. For the poloidal coils, a cable-in-conduit conductor (CICC) is used. A forced-flow of supercritical helium at 4.4–4.7 K circulates inside the conductor as a coolant. The poloidal coils have maintained stable operation for fourteen years.

An important issue for the stable operation of forced-flow-cooled coils is maintaining the hydraulic characteristics for long periods. Because the CICC has narrow cooling channels, impurities in the helium, such as metal pieces, ice of impurity gases and oil from the helium compressors, might obstruct the circulated helium flow in the conductor [2]. The flow obstruction results in degradation of the stability of the conductor. In the worst case, the coil could be quenched.

We have continuously monitored the pressure drop between the inlet and outlet of each coil since 1998 when the LHD operation started [3]. The observed pressure drops were converted into dimensionless friction factors to eliminate the effects of flow rate and the configuration. The friction factor was compared with commonly used empirical formula to investigate interannual changes.

2. Coils and Conductors

The poloidal coil system consists of three pairs of circular solenoids named the inner vertical (IV), inner shaping (IS) and outer vertical (OV) coils. To distinguish lower and upper coils, the characters ‘-L’ and ‘-U’ are added to the abbreviation. For example, IV-L means the lower IV coil. The coils are formed from continuous conductors wound into two-layer coils called a double-pancake, with eight double-pancakes stacked, molded and electrically connected in serious. A helium entrance is located at the middle of each double-pancake, and helium passes out of the two ends of the double-pancake. A coil has sixteen parallel helium flow paths.

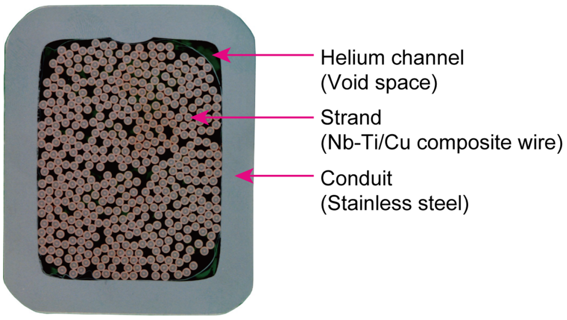

Fig. 1 Cross-secional image of the conductor for the IV coils.

The cross section of the conductor for the IV coils, as an example, is shown in Fig. 1. The conductors are CICC type with 486 Nb-Ti/Cu composite wires. The strands are twisted with five stages to produce a cable. The cable is covered with a round-cornered rectangular conduit made of stainless steel. Helium flows through narrow channels between the strands. The parameters associated with the hydraulic characteristics are listed in Table 1.

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[*)] This article is based on the presentation at the 21st International Toki Conference (ITC21).

Table 1 Parameters assoiated with hydraulic characteristics of the LHD poloidal coils.

	IV	IS	OV
Conductor dimension (mm)	23.0 × 27.6	23.0 × 27.6	27.5 × 31.8
Conduit thickness (mm)	3.0	3.0	3.5
Strand diameter (mm)	0.76	0.76	0.89
Number of strands	486	486	486
Void fraction in a cable space	0.38	0.38	0.38
Hydraulic diameter (mm)	0.43	0.43	0.50
Average diameter of the coil (m)	3.6	5.64	11.1
Number of layers	16	16	16
Number of turns per layer	15	13	9
Length of a flow path (m)	170	230	314
Number of flow paths	16	16	16
Mass flow rate per coil at 300 K (g/s)*	2	2	2
Mass flow rate per coil at 4 K (g/s)*	54–55	53–64	55–57

* at the 15th campaign

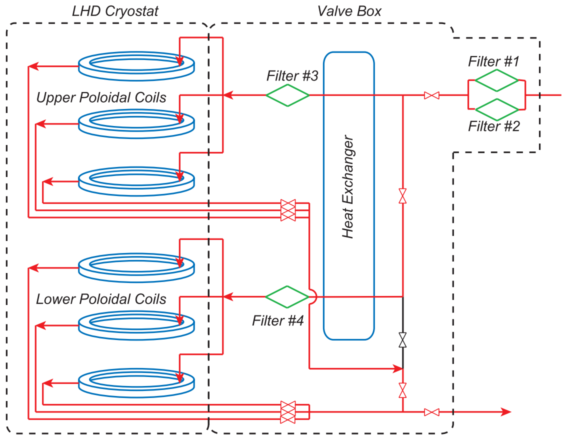

Fig. 2 Helium coolant flow diagram. Red lines show helium flow during initital cooling.

3. Cooling Methods and Filters

The helium coolant comes from a refrigerator and goes into a valve box (VB) positioned close to the LHD cryostat. Helium then flows through all the coils in parallel as shown in Fig. 2. The VB has a heat exchanger to remove the heat input from the refrigerator to the VB and has several valves to control the pressure and flow rate, as well as four mesh filters (filters #1 to #4 in Fig. 2). Filters #1 and #2 can be switched when one or other is clogged. The clogged filter can be warmed up independently and evacuated to clear impurities. If the impurity is ice of water and air, it can be removed from the filter. Filters #3 and #4 are backup and stationary. The mesh sizes are 5 µm for filters #1 and #2 and 20 μm for filters #3 and #4.

At the beginning of an experimental campaign, the coils are cooled down while the temperature difference between the inlet and outlet was controlled to within 50 K. It takes about a month to cool all the coils down to 5 K. The LHD has experienced fifteen experimental campaigns with a cool-down and warm-up over fourteen years. In other words, the coils have been cooled fifteen times from room temperature down to cryogenic temperature.

4. Hydraulic Characteristics

The hydraulic characteristics have been investigated by means of the Darcy friction factor. The relationship between the pressure loss (ΔP) and friction factor (λ) can be expressed as

$$\Delta P = \lambda(L/D_\mathrm{h})(\rho V^2/2), \tag{1}$$

where L is the length of the flow path, D_h is the hydraulic diameter, ρ is the density of helium and V is the average velocity. D_h is defined as

$$D_\mathrm{h} = 4A/P, \tag{2}$$

where A is the channel cross-sectional area and P is the wetted perimeter. The perimeter is the sum of the circumferences of strands and the inside of a conduit. The friction factor depends on the Reynolds number (R_e) defined as

$$R_\mathrm{e} = \rho V D_\mathrm{h}/\mu, \tag{3}$$

where μ is the coefficient of viscosity. ρ and μ, which depend on pressure and temperature, were calculated using the software HEPAK [4].

Figure 3 shows the hydraulic characteristics (friction factor versus Reynolds number) of the IV-L coil at room temperature and at cryogenic temperature for fourteen years. All the data in Fig. 3 (b) were obtained at midnight on every weekend to eliminate the effect of coil excitations and other heat loads. The data for the first campaign in 1998 were omitted from the figures because a rated mass flow rate could not be achieved due to a defect in the helium outlets.

The solid line in Fig. 3 (a) represents the empirical relationship proposed by Katheder [5]. The formula is expressed as

$$\lambda_\mathrm{KF} = \upsilon^{-0.72}(19.5R_\mathrm{e}^{-0.88} + 0.051), \tag{4}$$

where υ is the void fraction in a cable space. All the data at room temperature follow $0.7\lambda_\mathrm{KF}$ (dotted line in the figure). As described previously [3], a complete laminar flow

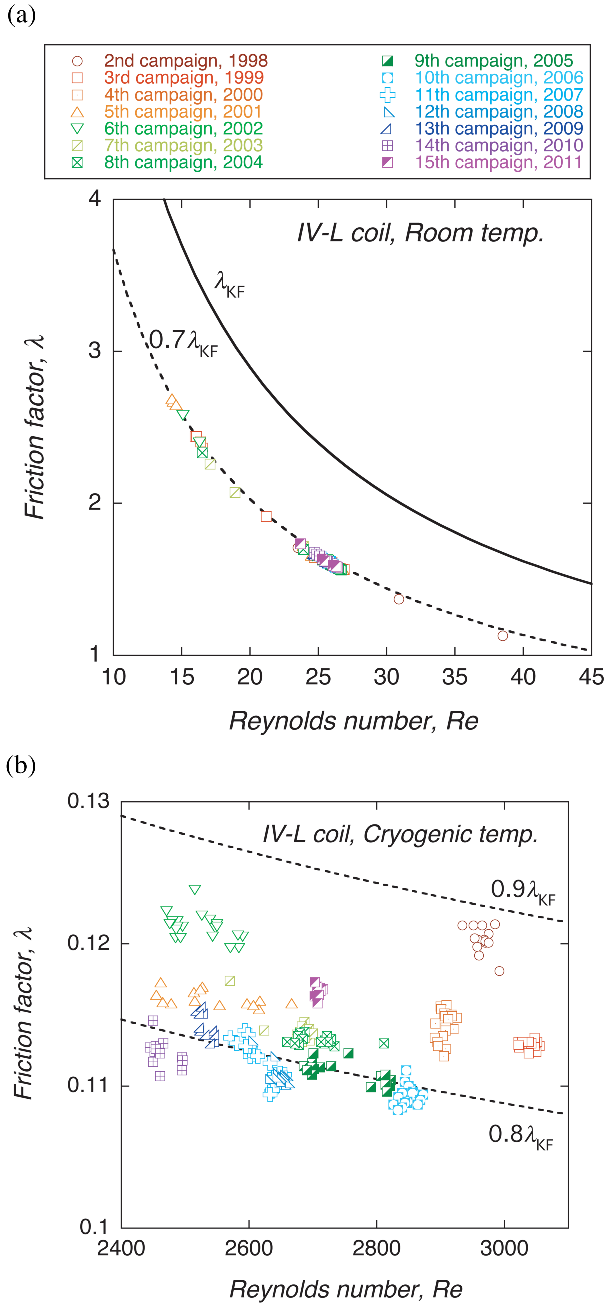

Fig. 3 Hydraulic characteristics (a) at room temperature and (b) at cryogenic temperature for the IV-L coil.

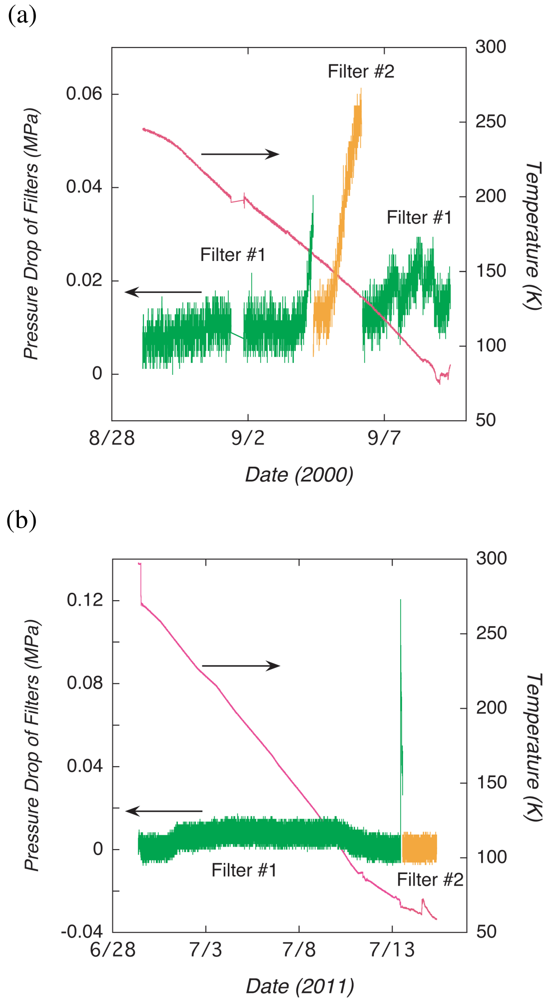

Fig. 4 Cooling curve (red) and pressure drop of the filters #1 (green) and #2 (orange) (a) in the fourth and (b) in the fifteenth cool-down.

was observed when the Reynolds number was less than 30, though the transition from a laminar flow to a turbulent flow is not well-defined for a CICC. The friction factor for a laminar flow depends on only the geometry of the cooling channels in a cable space. Therefore, the long-term observation suggests that no extraneous solid particles have been trapped in the cooling channels at room temperature.

At cryogenic temperature, a discontinuous change in the friction factor was observed for every campaign, as shown in Fig. 3 (b). No obvious variation was observed over the period of each campaign. This suggests that solidified gases (nitrogen, oxygen and hydrocarbon) or vapors (water and oil) may obstruct a portion of the helium channels. Actually, the mesh filters (#1 and #2) trapped impurities during cool-down of the coils, confirmed by monitoring the pressure drop of the filters. During the past fourteen years, the filters clogged in the first three years (1998–2000) and in the most recent campaign (2011). Figure 4 shows the pressure drops of the filters during cool-down. In the fourth cool-down, filter #1 was gradually obstructed from 170 K, and the filter was switched to #2. Filter #2 was then also obstructed. Filter #1 could be cleaned by individual warm-up and evacuation. This confirmed that the obstruction of the filters was caused by solidified gasses or vapors in the cooled helium. In the fifteenth cool-down, the pressure drop of filter #1 suddenly increased at 70 K, and the filter was switched to #2, as shown in Fig. 4 (b). A difference in temperature at which the filter was clogged was observed, which may be related to the freezing point of impurities. This suggests that the dominant impurities were different between the fourth and fifteenth cool-downs.

Figure 5 shows the variation in the average λ/λ_{KF} over each campaign period for the six coils. The difference between coils may be caused by surface conditions on the

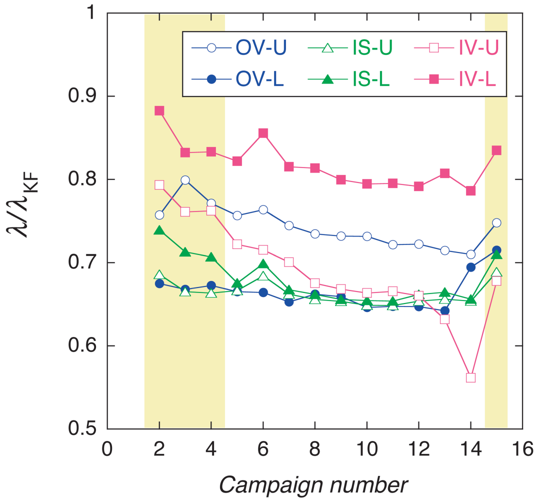

Fig. 5 Interannual trends in friction factor over fourteen years.

strands because helium flow is turbulent at cryogenic temperature. The yellow hatching shows the campaigns for which the inlet filters clogged during cool-down. The friction factor tended to be higher in campaign where the filters clogged. The friction factor of all the coils increased in the 15th campaign, for which the filter clogged as described above. The interannual variation may be caused by tiny solid particles passing through the filters.

As a result, the initial hydraulic characteristics can be maintained for fourteen years though some variation appeared. The filters probably played an important role in avoiding obstruction of the coils themselves.

5. Conclusions

The long-term continuous monitoring of hydraulic characteristics of the LHD poloidal coils demonstrates that the initial condition can be maintained without flow obstruction for long periods. The inlet filters can effectively remove solidified gases or vapors that might cause obstruction of the helium flow path in the coils. We plan to continue to monitor the hydraulic characteristics for stable operation.

Acknowledgements

This work was supported in part by MEXT of the Japanese government under Grant NIFS11ULAA703 and NIFS11UFAA003. The authors wish to thank the members of the LHD device engineering group for their technical assistance.

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