§4. Estimation of Effective Heat Transfer of the LHD Helical Coils in Comparison with Its Model Coil

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The effect of lowering temperature on the minimum propagating current was examined with a model coil of the LHD helical coil [1]. The propagation of a normal-zone are detected by voltage taps on the conductor. Normal-zones are initiated by a tape heater inserted between the conductor and the spacer. The minimum propagating current is clearly improved in subcooled helium than in saturated helium. In addition, the cryogenic stability in saturated helium is improved by being subcooled once. The reason is not clear, but one possible reason is the enlargement of the wetting area at the narrow space around the conductors.

Average propagation velocities in tested turns are shown in Fig. 1. The propagation velocities at the same current are slower at the lower temperature in subcooled helium. From the quasi-static heat balance equation, the propagation velocity v_g is expressed as

$$v_g = \sqrt{phk/A} \cdot (\Gamma - 2) \Big/ \left(F \cdot c\sqrt{\Gamma - 1}\right)$$
$$\Gamma = \rho I^2 \Big/ Aph\left((T_c + T_s)/2 - T_b\right) \qquad (1)$$

where p, A, h, k, ρ, c, I, T_c, T_s, T_b, F are the perimeter, cross-sectional area, equivalent heat transfer coefficient, thermal conductivity, resistivity, specific heat, current, critical temperature, current sharing temperature, bath temperature, and factor of effective heat capacity, respectively. The ρ, T_c, and T_s are dependant on the magnetic field, and the ρ is calculated from the measured peak voltage of the voltage taps in the model coil including the effect of the slow current diffusion. The k and c are averages of the composite conductor. The values of F and h are surveyed to fit the experimental results. Figure 2 shows the calculated result for F of 0.6. The values of h are determined to fit to the measured velocity around 10 m/s. The h in saturated helium of 4.4 K before being subcooled is estimated to be 0.51 kW/m^2/K, and it is improved by 20% after being subcooled. Furthermore, it is improved by more 25% by being subcooled to 3.5 K.

An additional cooler with the refrigerating power of 280 W at 3.0 K is installed in the inlet line of the LHD helical coils. The inlet and outlet temperatures of the coils are successfully lowered to 3.2 K and 3.8 K, respectively, with a mass flow of 50 g/s [2]. A propagation of a normal-zone was observed at 11.4 kA from the bottom of #10 sector, from which the propagation was observed several times in saturated helium. The propagation velocity in the LHD can be estimated from the time delay of the peak voltage of pickup coils that are installed along the helical coils by the pitch of 60 degrees in the poloidal angle [1]. Typical examples of the estimated velocities are shown in Fig. 1. The propagation velocity is faster at the higher magnetic field area. The slowest velocity in the saturated helium at 4.4 K is 6 m/s, which is the same as that of the model coil in saturated helium before subcool. The slowest value is determined by the effect of uncontinuity of cooling condition. The slowest propagating velocity in the model coil is faster at lower temperatures. It should be caused by the change of the characteristic length of temperature distribution in the conductor that is shorter with the higher heat transfer.

The equivalent heat transfer of the LHD helical coil is estimated with the same method, as shown in Fig. 2. The estimated h at the bottom of the coil is 0.48 kW/m^2/K in saturated helium, which is close to that of the model coil. It is improved by 20% under the subcooling operation. Its improvement is less than the model coil by being subcooled. Therefore, the local temperature of the innermost layers of the helical coil at the bottom is considered to be higher than the outlet temperature under the subcooling operation. It should caused by restriction of longitudinal flow near the innermost layers in the coil.

1) Imagawa, S. et al., Fusion Eng. Des., **81** (2006) 2583.
2) Imagawa, S. et al., IEEE Trans. Appl. Supercond. **18** (2008) 455.

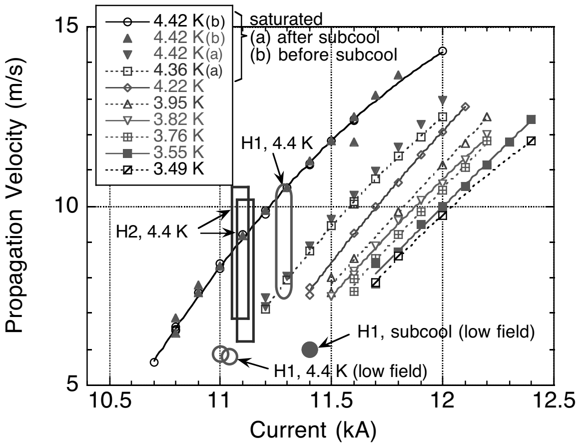

Fig.1. Comparison of propagation velocities in the LHD helical coil and the model coil.

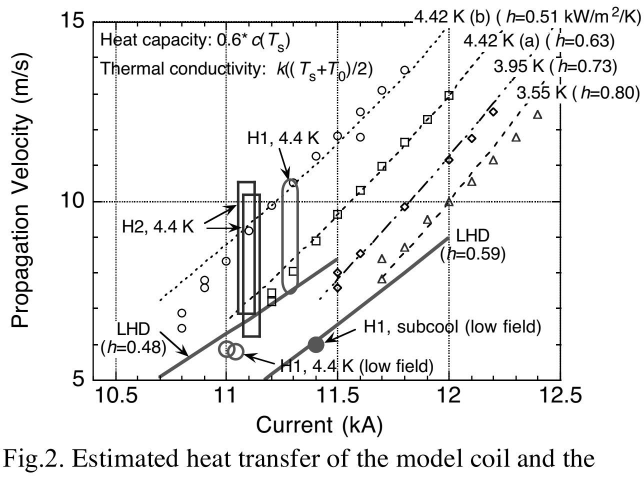

Fig.2. Estimated heat transfer of the model coil and the helical coil. The symbols are measured propagation velocities.