§7. Estimation of Heat Generation during a Normal-zone Propagating and Recovering in the LHD Helical Coils

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One-side propagation of a normal-zone is observed in helical coils of the Large Helical Device and their model coil. At the current close to the minimum propagating current, a normal-zone propagates to only the downstream side of the current. At the higher currents, a normal-zone propagates to both sides with the slow upstream velocity that is almost half as downstream. Such large asymmetry in the propagation velocity observed in the experiments cannot be simulated by considering the induced current by Hall voltage.[1), 2)] In order to evaluate the amount of asymmetric heat generation, dynamic heat analyses with a finite differential method have been carried out.[3)] In this study, the calculation model is revised to estimate the effect of temperature rise of the CuNi layer, which covers an aluminum stabilizer, as shown in Fig. 1, to reduce the Hall currents with maintaining smooth current transfer from NbTi/Cu strands.

Since thermal conductivity in copper and aluminum is sufficiently high, the conductor is divided into 5 elements, as shown in Fig.1, which are (1) half of the copper sheath in the strands side (Cu1), (2) NbTi/Cu strands and PbSn solder (SC), (3) CuNi layer between the strands and the aluminum stabilizer (CuNi), (4) the aluminum stabilizer and the rest of CuNi layer (Al), (5) half of the copper sheath in the stabilizer side (Cu2). Since the thermal conductivity of CuNi is sufficiently low, its thermal conduction in the longitudinal direction (x-direction) is ignored. The size and conditions of the analysis model for the model coil is shown in Fig. 2. The spacer pitch is 54 mm with the wetted surface fraction of 67%, that is, the length of one cooled area is 36 mm. A heater for inducing a normal zone is attached to Cu1 at x=0, where the center of uncooled region is, with a thin epoxy layer. The equivalent heat capacity of the heater and the thickness of the epoxy layer are adjusting factors for the analyses.

Since the transfer current between the strands and the stabilizer crosses the external magnetic field, Hall voltage is induced along the conductor. In these analyses, direct interaction between the Hall voltage and the transport current is considered. The work is given by

$$W^{Al} = \int_0^{\ell} E_x I_x^{Al}(x)\,dx = \left(R_H^{Al} + R_H^{Cu}\right) B_z I_0^2 \Big/ 2a = W^{SC} \qquad (1)$$

with R_H^{Al}: Hall coefficient of aluminum (1.022×10^{-10} m^3/C), R_H^{Cu}: Hall coefficient of copper (-0.54×10^{-10} m^3/C), j: current density, B_z: magnetic field, I_0: transport current, l: length of transfer region, a: width of the strands. The works by Hall effect are negative at the upstream side of the transport current and positive at the downstream side. In addition, joule loss by the transfer current is given by $I_0^2(rR(t))^{0.5}$, with $R(t)$: resistivity of the stabilizer, r: resistance per unit length of the CuNi layer including contact resistance. Half of the loss is generated in the CuNi layer, and the rest is generated in the stabilizer. The characteristic length of current transfer is given by $(r/R(t))^{0.5}$, which is set at 25 mm in this analysis considering the high transient resistance of the aluminum during current diffusion. The normal zone is defined as the area where the temperatures of SC are higher than the current sharing temperature. The middle of the current transfer region is set at the edge of the normal zone.

The calculated results are in good agreement with the experiments with reasonable following parameters; a) thermal conductance between the strands and CuNi layer is the half of ideal value, b) heat transfer efficiency is 70% and 90% of the measured data with a conductor sample for before and after being subcooled, respectively, c) the heat generation or absorption by the Hall effect of transfer current is $\pm(R_H^{Al}+R_H^{Cu})BI^2/(2a)\times0.8$. A representative result is shown in Fig. 3, in which the heater inputs are 100 W×20 ms at the currents lower than or equal to 11.4 kA and 50 W×20 ms at the higher currents.

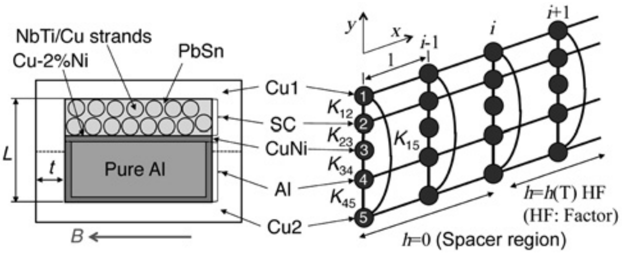

Fig. 1. A calculation model of the helical coil conductor, where k_{12}, k_{23}, k_{34}, and k_{45} are thermal conductances.

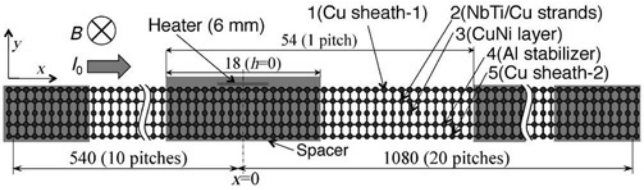

Fig. 2. The size and conditions of the analysis model.

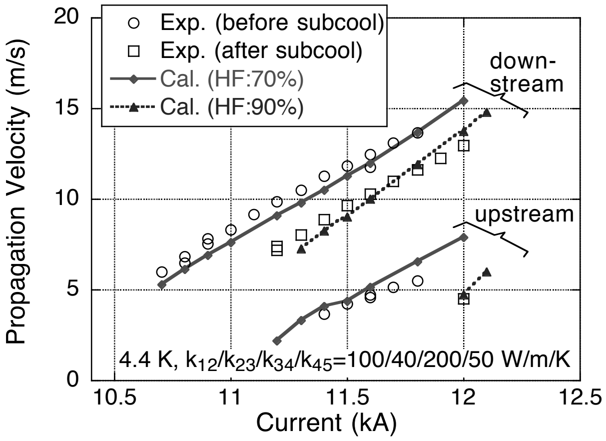

Fig. 3. The measured and calculated propagation velocity at 4.4 K. HF is the ratio of heat transfer to the measured value with a short conductor sample.

1) Shirai, Y. et al.: IEEE Trans. Appl. Supercond. 18 (2008) 1275.
2) Kawawada, N., et al.: IEEE Trans. Appl. Supercond. 16 (2006) 1717.
3) Shirai, Y. et al.: Annual Report of NIFS (2012) 273.