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

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A conductor of LHD helical coils consists of NbTi/Cu strands, a pure aluminum stabilizer clad with Cu-2%Ni layer, and a copper sheath. One-side propagation of a normal-zone has been observed several times at the currents around 11.0 kA. The normal-zones propagated to one side with the recovery from the opposite side except for one case of propagating to both sides at 11.4 kA. One-side propagation is also observed in conductor samples and in a model coil of the helical coil. At the currents 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. Simulation studies have been carried out with considering the Hall effect during the current transfer between the superconductor and the aluminum stabilizer. However, such large asymmetry in the propagation velocity observed in the experiments cannot be simulated yet.[1), 2)] In order to evaluate the amount of asymmetric heat generation for understanding the mechanism, dynamic heat analyses with a finite differential method have been carried out.

In the helical coil conductor, the transport current flows mainly in the aluminum stabilizer when normal state. Hall voltage is induced in the aluminum, and an additional loss is induced by the Hall currents that flow through the NbTi/Cu strands and the copper sheath. In order to reduce the Hall currents with maintaining smooth current transfer, the aluminum stabilizer is covered with Cu-2%Ni layer, as shown in Fig. 1. Comparing the measured magneto-resistance with the theory, the resistance of the Hall current circuit is as twice as the ideal value. The additional resistance should be the contact resistance between the CuNi layer and the NbTi/Cu strands or between the CuNi layer and the copper sheath.

Since thermal conductivity in copper and aluminum is sufficiently high, the conductor is divided into 4 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) the aluminum stabilizer and the CuNi layer (Al), (4) half of the copper sheath in the stabilizer side (Cu2). The spacer pitch is 54 mm with the wetted surface fraction of 67%. A heater is attached to Cu1 at x=0, where is the center of uncooled region, 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

$$W_{CT} = I_0^2 \sqrt{R(t)\cdot r} \qquad (2)$$

with $R(t)$: resistivity of the stabilizer, r: resistance per unit length of the CuNi layer including contact resistance. Half of the W_{CT} is generated in the CuNi layer, and the rest is a Joule loss 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.

Transient Joule losses in the elements are calculated using analytical equations for one-dimensional current diffusion into the aluminum and copper. The suitable parameters were surveyed to simulate the experimental data both of the minimum propagating currents and of the propagation velocities. 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 75-90% of the measured data with a conductor sample, as shown in Fig. 2.

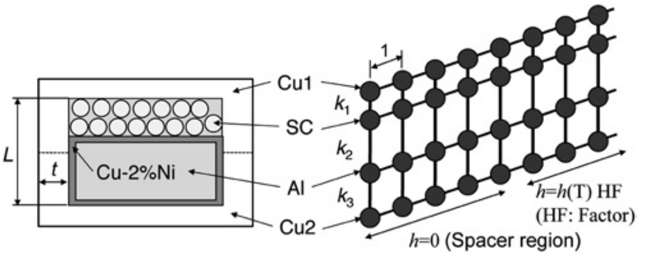

Fig. 1. A calculation model of the helical coil conductor, where k_1, k_2, and k_3 are transverse thermal conductivities.

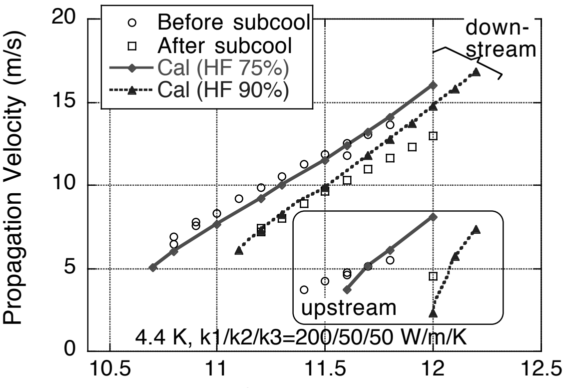

Fig. 2. The measured and calculated propagation velocity at 4.4 K. HF is the ratio of heat transfer to the measured value.

1) Shirai, Y. et al.: IEEE Trans. Appl. Supercond. 18 (2008) 1275.
2) Kawawada, N., et al.: IEEE Trans. Appl. Supercond. 16 (2006) 1717.