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Thermal Contact Conductance Between the Bundle and the Conduit in Cable-in-Conduit Conductors

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***Abstract*—Temperature rise in a quenching cable-in-conduit conductor is strongly affected by thermal contact conductance between the bundle and conduit. To evaluate this temperature rise, conductance is measured by using two experimental techniques. In the first experiments, we apply a current to a short conductor cooled to liquid nitrogen temperature and observe the temperature rise of the bundle and conduit. The conductance is calculated from the temperature difference. In the second experiments, contact conductance is directly measured under compressive pressure at room temperature by using a small copper block with heaters. The results show that the contact conductance is affected by surface pressure and is almost independent of the conductivity of ambient gas. Therefore, to evaluate temperature rise in a quenching conductor, it is necessary to measure conductance under a surface pressure equivalent to an electromagnetic force.**

***Index Terms*—Cable-in-conduit conductor, quench, superconducting cables, temperature rise, thermal contact conductance.**

I. INTRODUCTION

A cable-in-conduit conductor, because of its high stability, rigidity and dielectric strength, is a strong candidate for large applications of superconducting magnets such as fusion reactors and magnetic energy storage. However, the maximum temperature rise during a quench is higher than that of a pool-boiling-cooled conductor. In the case of the cable-in-conduit conductor, the available heat capacity of helium is limited by the conduit wall. In addition, heat transfer to the conduit is restricted due to thermal contact resistance between the bundle of strands and the conduit wall. For these reasons, only the heat capacity of the strands is used for the calculation of the maximum temperature rise in a conservative design. The maximum temperature calculation determines the volume of copper in the case of large magnets [1]. Separate copper wires are sometimes added if the copper fraction in the superconducting strands is limited by the fabrication processes. However, excessive copper causes a decrease in the current density and an increase in cost. A consideration of the available heat capacity of the conduit is necessary to ensure high current density and low cost.

Here we present two simple techniques to evaluate the thermal contact conductance (that is, the reciprocal of thermal resistance) between the bundle and the conduit. In the first experiments, we apply a current to a short conductor sample cooled to liquid nitrogen temperature. Performing the experiment with liquid nitrogen is more convenient than with liquid helium because a special cryostat and current leads are not required. Also, measuring the temperature rise above the liquid nitrogen temperature can provide useful information because the heat required for a rise from 4 to 80 K is only 7 percent of that for a rise from 4 to 300 K for copper and stainless steel. The second technique measures the thermal contact conductance under surface pressure at room temperature. From the experiments, we have obtained important information about the effects of surface pressure and ambient gas.

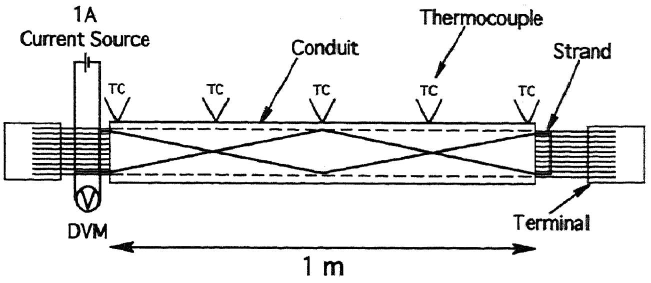

Fig. 1. Schematic arrangement for the measurement of temperature rise in the current-carrying conductor.

The experimental procedures and results for the two techniques are presented in Section II and III, respectively. The applicability of the techniques to actual conductors is also discussed in Section IV.

II. MEASUREMENT OF TEMPERATURE RISE IN THE CURRENT-CARRYING CONDUCTOR

A. Sample and Experimental Procedures

The cable-in-conduit conductor used in the experiments described here was developed as the prototype of the Large Helical Device conductor [2]. The dimensions of the conductor sample are 17.0 mm by 22.5 mm, with an outer-corner radius of 6 mm. The thickness of the conduit is 1 mm. Encased in the conduit are 486 Nb-Ti/Cu/Cu-Ni composite strands with a void fraction of 40%. A unique feature of the conductor is that all strands are coated with 10-μm-thick Formval (polyvinyl acetal resin).

The experimental arrangement is shown schematically in Fig. 1. A 1.6-m-long conductor was prepared and 0.3 m of the conduit was cut off from each end. The strand ends were soldered to copper terminals at each end, and the copper terminals were connected to a 6 kA power supply. To measure average temperature in the bundle, two strands were extracted at one end and the strand ends were soldered to each other. At the other end, the two strands were connected to a 1 A current source and digital voltmeter (DVM). Because the 1 A current loop was electrically isolated from the other strands, we could

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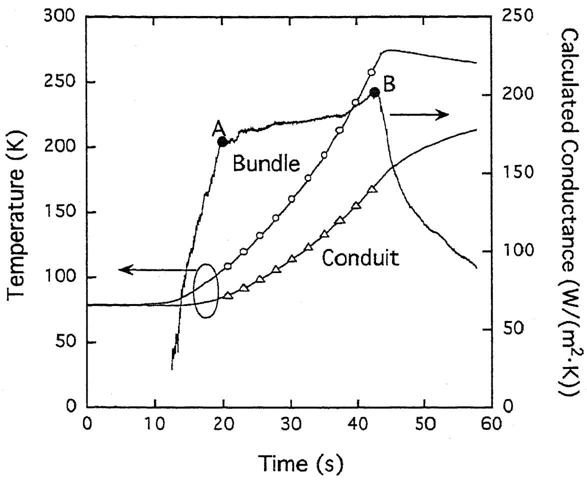

Fig. 2. Temperature rise measured at 6 kA.

compute the average temperature of the bundle region from the measured voltage. The average temperature of the conduit was obtained with ten thermocouples attached to the outer surface.

In the experiment, the sample was first cooled with liquid nitrogen in a foam tub. After lifting the sample out of the liquid, a current of up to 6 kA was applied until the temperature of the bundle reached 270 K.

B. Experimental Results

Fig. 2 shows the temperature rise measured at 6 kA. While current was being supplied, the temperature of the conduit increased more slowly than that of the bundle, and temperatures at the center and both ends of the conduit were almost the same. After current was shut off, the temperature distribution in the longitudinal direction became nonuniform. The cause of the nonuniform distribution was heat leakage to the terminal, which was low during the current feed because strands near the terminals also generated Joule heat.

The temperature difference between the bundle and the conduit confirms that the thermal contact resistance at the interface affects the temperature rise. We then evaluated thermal conductance with the following equations:

$$C_{conduit}\frac{dT_{conduit}}{dt} = hS(T_{bundle} - T_{conduit}), \quad (1)$$

$$C_{bundle}\frac{dT_{bundle}}{dt} = RI^2 - hS(T_{bundle} - T_{conduit}), \quad (2)$$

where C is the heat capacity per unit length, T is the temperature, h is the conductance, S is the perimeter inside the conduit wall, R is the resistance per unit length, and I is the current. The subscripts *conduit* and *bundle* denote the components. In (1), heat leakage by natural convection can be neglected because the temperature of the conduit at the center did not decay for a long period of time after current shutoff, as shown in Fig. 2. Symbol $T_{conduit}$ is defined as the average temperature.

Using (1), we calculated the conductance as shown in Fig. 3. The calculated conductance steeply increased until the bundle temperature reached 100 K (points A in Figs. 2 and 3). Then, a shift to a gradual change was observed. In the initial process, a temperature gradient may have been formed inside the conduit.

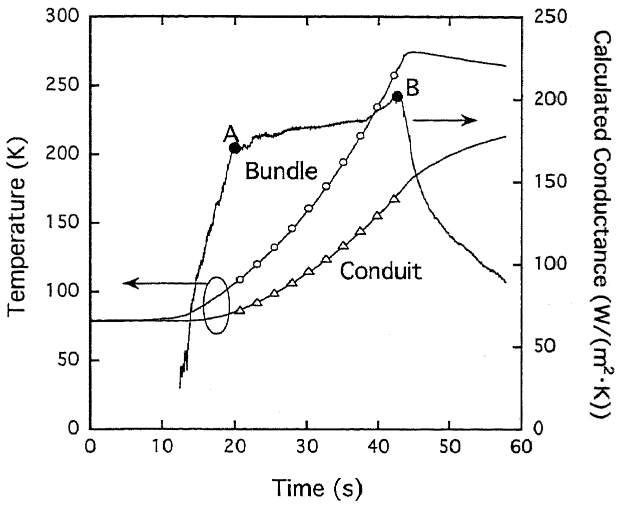

Fig. 3. Calculated thermal contact conductance between the bundle and the conduit by using formula (1). The open circles and triangles represent the calculated temperature rise by using a conductance of 186 $\mathrm{W/(m2 \cdot K)}$ with formulas (1) and (2).

After the shutoff (points B in Figs. 2 and 3), the calculated conductance decreased. In this region, the heat leakage to the terminal as described previously may have affected the evaluation. As a result, the calculated conductance in the range from points A to B can be considered as the actual contact conductance. The average of the calculated conductance is 186 $\mathrm{W/(m^2 \cdot K)}$. Using this value in (1) and (2), we calculated the temperature rise. The results are plotted as open circles and triangles in Fig. 3. The evaluated temperature rise agrees well with the measured temperature. It should be noted that the temperature rise can be evaluated by using only one conductance value in the temperature range from 100 to 270 K. This also suggests that the measurement of conductance at room temperature can be applied to an evaluation at cryogenic temperatures. We can then propose another technique as described in the next section.

III. MEASUREMENT OF THERMAL CONTACT CONDUCTANCE UNDER SURFACE PRESSURE

A. Sample and Experimental Procedures

The cable-in-conduit conductor used in the measurement of thermal contact conductance is the same conductor used for the inner vertical coil of the Large Helical Device [3]. The dimensions of the conductor sample are 23.0 mm by 27.6 mm. The thickness of the conduit is 3 mm. Encased in the conduit are 486 Nb-Ti/Cu composite strands with a void fraction of 38%. The surface of the strands is bare copper, which differs from the conductor used in the first experiments. The bundle was wrapped with a stainless steel tape (0.05 mm thick and 25 mm wide).

The experimental arrangement is schematically presented in Fig. 4. The lower half of the conduit was cut from the conductor, and the lower surface of the bundle, wrapped with tape, was attached to a copper block equipped with two heaters. The copper block was 50 mm long and 17.5 mm wide. The copper block and lower half of the bundle were then covered with a fiber-reinforced plastic (FRP) block on a load cell. A compressive load of up to 3 kN was applied vertically by using a mechanical testing instrument. The resulting maximum surface pressure at

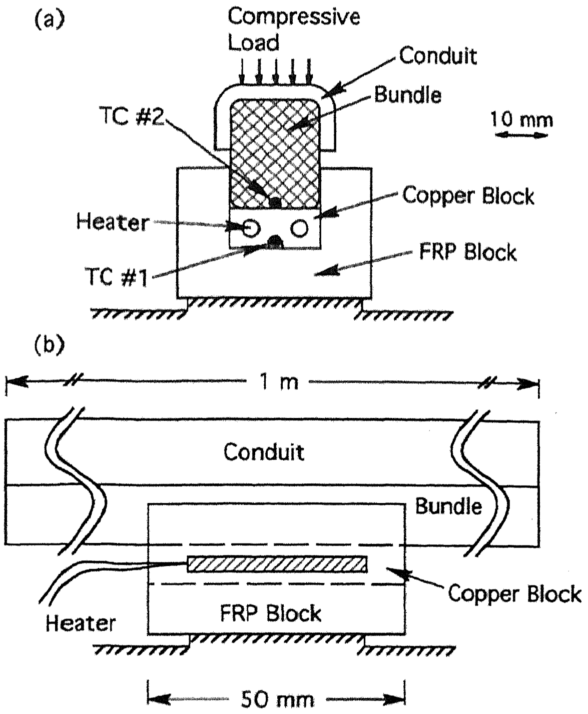

Fig. 4. Experimental arrangement for measuring thermal contact conductance under surface pressure; (a) cross-sectional and (b) side view.

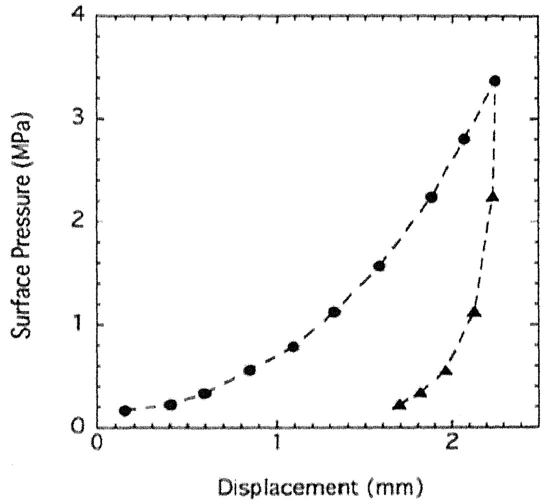

Fig. 5. Surface pressure versus displacement curve.

the upper surface of the block was 3.4 MPa. Fig. 5 shows the relationship between the surface pressure and displacement. The filled circles and triangles indicate measurement points during the loading and unloading processes, respectively. The original state of the bundle covered with a conduit corresponds to a displacement of 1.6 mm in Fig. 5.

To measure conductance, a transient technique was applied [4]. First, the copper block was heated to 340 K. After shutting off the heat, we observed the decay of temperatures in the copper block and the strands touching the block using thermocouples (TC #1 and #2 in Fig. 4). The conductance was evaluated with the following equations:

$$C_{block}\frac{dT_{block}}{dt} = -hS(T_{block} - T_{strand}) - Q_{leak}, \quad (3)$$

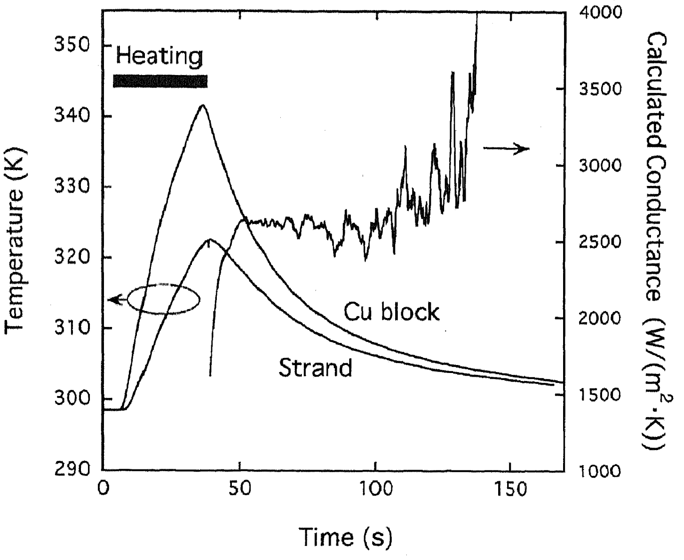

Fig. 6. Observed temperatures and calculated conductance under a surface pressure of 3.4 MPa.

where C_{block} is the heat capacity, h is the conductance, and S is the area of the upper surface of the block. Symbols T_{block} and T_{strand} represent the temperatures of the block and strands, respectively. The error due to the temperature gradient in the copper block was confirmed to be less than 4% by FEM analyses. Heat leakage to the surroundings, Q_{leak}, was measured by replacing the conductor with cotton as a thermal insulating material. Then, heat leakage was obtained by using the exponent of the temperature decay, m, as:

$$Q_{leak} = C_{block}m(T_{block} - T_a), \quad (4)$$

where T_a is the ambient temperature.

B. Experimental Results

Fig. 6 shows a typical example of observed temperatures and conductance calculated by (3) under a surface pressure of 3.4 MPa. We can find the region in which the calculated conductance is constant and consider the mean value in this region to be the actual conductance. In the case of Fig. 6, the contact conductance was approximately 2600 $W/(m^2 \cdot K)$. All measured data are presented as a function of surface pressure in Fig. 7. The results confirm that the contact conductance is strongly affected by the surface pressure.

To examine the effect of ambient gas, we also measured conductance in an atmosphere of helium under a surface pressure of 3.4 MPa and compared it with conductance in an atmosphere of air. Helium has higher thermal conductivity than air by a factor of six. The results are shown as a filled rectangle and triangle in Fig. 7. The conductance was found to be affected less by gas than by surface pressure.

The observed conductance in the first experiments was much lower than that in the second experiments. The most probable cause is the difference in measuring methods for strand temperature. In the first experiments, the temperature gradient in the bundle region may have resulted in an underestimation of the conductance at the conduit wall. Moreover, the insulation on the strand surface and the difference in the void fraction may also have affected conductance.

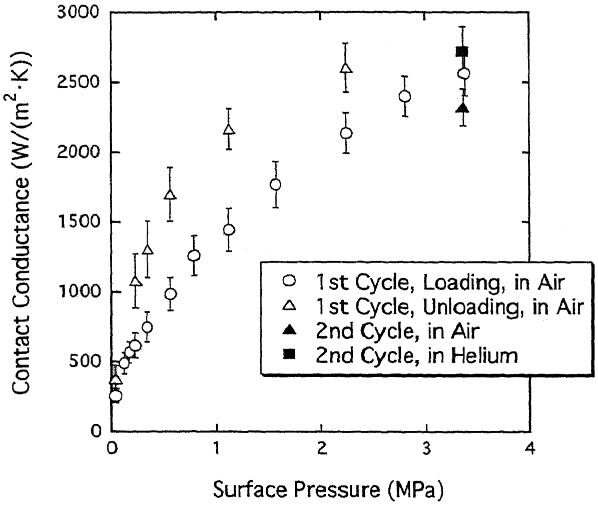

Fig. 7. Contact conductance as a function of surface pressure.

IV. DISCUSSION

The subject of contact conductance is generally discussed in the field of electronics because heat from devices is commonly dissipated by the attachment of a heat sink. In the calculation of conductance for solid-to-solid contacts, the following relationship has been proposed [5]:

$$h = h_c + h_g. \quad (5)$$

Contact conductance, h_c, is related to conduction across the true contact points. It depends on the properties of the materials in contact (conductivity and hardness) and the surface pressure. On the other hand, gap conductance, h_g, expresses conduction across an interstitial gas. It depends on the conductivity of the gas and the thickness of the gap. In our experiments, conductance across contact points probably dominated the observed conductance because the effect of the ambient gas was less than that of surface pressure, as shown in Fig. 7. The temperature dependency of the conductance, as shown in Fig. 3, can be explained similarly. The conductance increased by only 20% with an increase in temperature from 100 to 270 K even though the conductivity of nitrogen increased by a factor of 2.5. This also confirms that the contribution of the gap conductance was small.

These results suggest that the technique for measuring conductance described in Section III can be applied to an evaluation of temperature rise in a quenching conductor because the conductance is relatively independent of the gas conductivity. However, the effect of surface pressure must be considered. In actual conductors, an electromagnetic force is applied to the bundle. On a conduit surface subjected to this force, the conductance will increase. Conversely, on the opposite side, conductance will decrease and approach zero as the bundle separates from the conduit wall. In this case, the effect of convection must be accounted for by using another analytical method.

V. CONCLUSION

To evaluate temperature rise in a quenching cable-in-conduit conductor, we measured the thermal contact conductance between the bundle and the conduit using two experimental techniques. First, a current was applied to a short conductor cooled to liquid nitrogen temperature. The conductance, obtained from the temperature difference between the bundle and the conduit during temperature rise, was nearly independent of temperature. In the second experiments, conductance was measured under surface pressure at room temperature. The results confirmed that the conductance is strongly affected by the surface pressure. The effect of the conductivity of ambient gas was relatively small. From these results, we conclude that it is necessary to measure the conductance under a surface pressure equivalent to the expected electromagnetic force.

REFERENCES

[1] K. Yoshida, H. Takigami, and H. Kubo, "Analytical studies on the hotspot temperature of cable-in-conduit conductors," *Cryogenics*, vol. 41, pp. 583–594, 2001.

[2] K. Takahata *et al.*, "Experimental results of the R&D forced-flow poloidal coil (TOKI-PF)," *Fusion Engineering and Design*, vol. 20, pp. 161–166, 1993.

[3] K. Takahata, T. Mito, H. Chikaraishi, S. Imagawa, and T. Satow, "Coupling losses in cable-in-conduit conductors for LHD poloidal coils," *Fusion Engineering and Design*, vol. 65, pp. 39–45, 2003.

[4] I. S. Lisker, S. V. Solovyev, B. P. Axcell, B. R. Varlow, and K. Donnelly, "A transient technique for measuring the thermal conductivity of non-metals," *Experimental Thermal and Fluid Science*, vol. 25, pp. 377–382, 2001.

[5] M. M. Yavanovich, J. R. Culham, and P. Teertstra, "Calculating interface resistance," *Electronics Cooling*, vol. 3, pp. 24–29, 1997.