Measurement of Overall Thermal Conductance and Thermal Contact Resistance in No-Insulation ReBCO magnet

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Background

Electrical characteristics of NI coils are well described with a lumped circuit [2, 7] or distributed circuit model [8-11] with electric contact resistances between turns. Although thermal contact resistance (TCR) has strong influence on thermal stability of NI coils, its quantitative value is not well known unlike electric resistance. In conduction cooling system, TCR is related with cooling efficiency and temperature distribution inside the coils. When the NI coil is in a bath of liquid helium, TCR is related with thermal diffusion and quench propagation in the event of quench.

Objectives

- Measurement of overall thermal conductance using a model coil, which have no conduction plates and epoxy layer from 10 to 40 K
- Measurement TCR using the measured overall thermal conductance and published known transversal thermal conductivity of ReBCO
- Application of TCR to a coil with conduction plates and epoxy layers using FEM analysis

Conclusion

- In this study, the overall thermal conductance was measured with a NI ReBCO coil and it was possible to quantitatively obtain TCR by analyzing experimental results with the previously reported thermal properties of ReBCO wire.
- The resultant TCR was $1.5x10^{-4}$ to $5x10^{-3}$ $K{\cdot}m^2/W$ depending to the temperature, which is 10 time larger than that from ReBCO wire itself.
- By applying the measured TCR to coil 2, which have conduction plate and epoxy layer to enhance the overall thermal conductance, it was possible to estimate the overall thermal conductance of coil 2 with reasonable accuracy.
- Since TCR may depend on radial stress distribution in the coils and structure of ReBCO wire, more quantitative measurement will be followed under various stress conditions by controlling the winding tension force with various ReBCO wires.

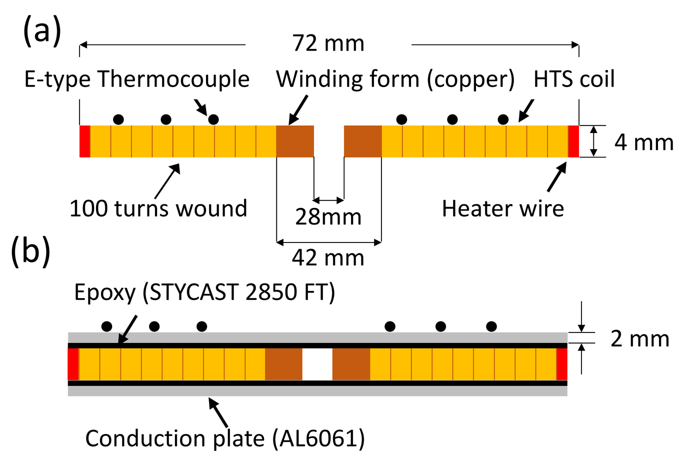
Experimental Apparatus

Test coils

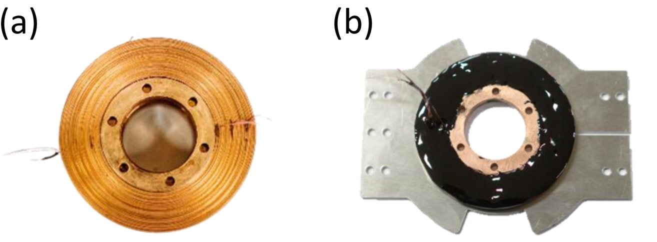
- A bare coil and a coil with conduction plates by NI winding scheme for the measurement of overall thermal conductance and TCR
- Six fine E-type thermocouples (AWG32) between winding turns to measure the coil temperature
- Ni-Cr heater wire outside the coil to make temperature gradient inside the coil

Specifications of test coil

Parameter	Value
Type of HTS wire	REBCO coated conductor
Width / thickness of wire	4 mm / 0.165 mm
I_c @ 77 K	150 A
Stabilizer thickness (copper)	36 µm
Wire manufacturer	SuNAM
No. of winding turns	100 turns
Winding tension force	50 N
Position of thermocouple	5, 23, 41, 59, 77, 95 turn
Heater material	Ni-Cr wire (15.7 Ω)
Experiment temperature	10, 15, 20, 30, 40 K
coil 1	coil only
coil 2	coil + conduction plate + epoxy



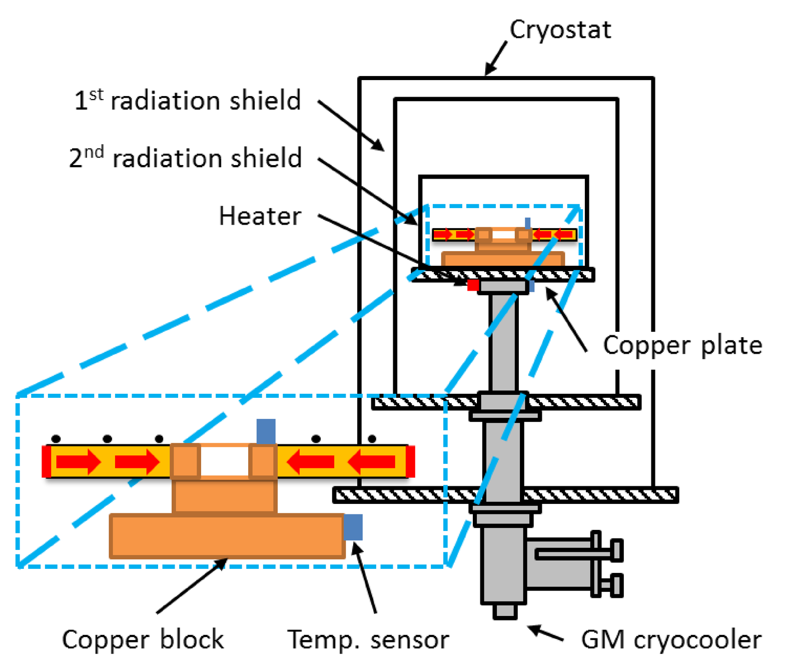
Configuration of the test coils: (a) coil 1 (coil only), (b) coil 2 (coil + conduction plate + epoxy layer)



Fabricated of the test coils: (a) coil 1 (b) coil 2

Conduction cooling measurement system

- Installation of the test coils on the 2nd stage cold head of a GM cryocooler (Sumitomo, RDK-415D) to be cooled down to measuring temperatures
- Minimization of radiation heat leak from environment by two radiation shields, thermally connected to the 1st and 2nd stage of cold head
- Installation of a cold junction at the 2nd stage of cold head for the precise measurement of the temperature
- Measurement of temperature variations by precise data acquisition system (National instrument, SCXI-1125)



Schematic diagram of thermal conductance measurement system

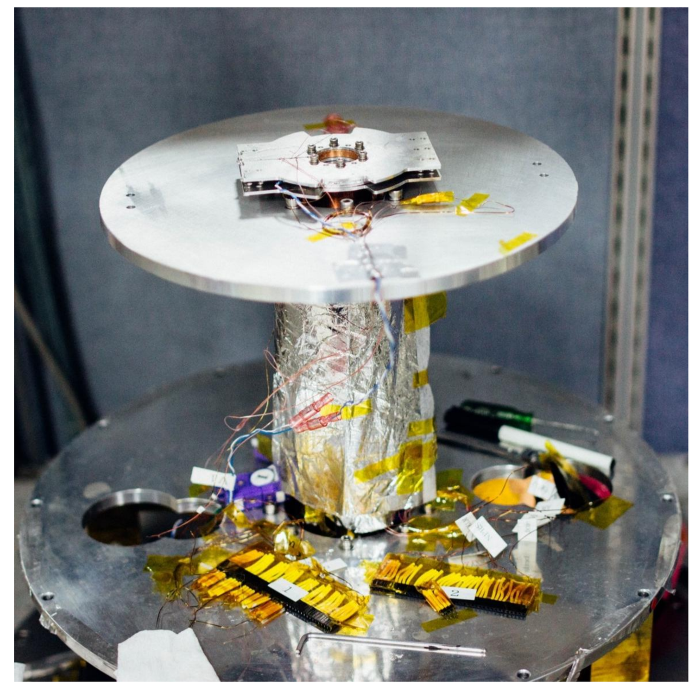
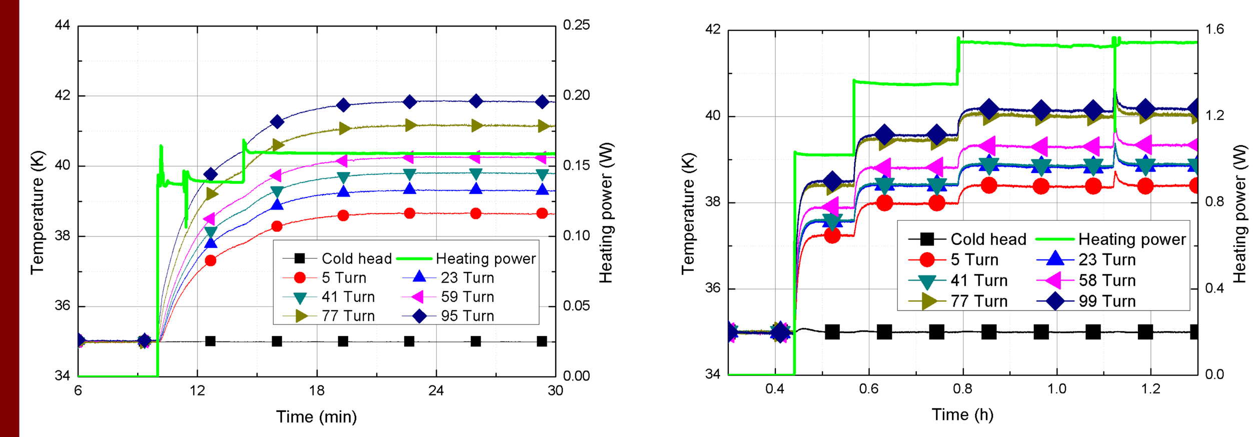


Photo of thermal conductance measurement system

Experimental Results

Overall thermal conductance



Temperature variations for the applied heating of (a) coil 1 (b) coil 2

- Determination of heating power to make 5 K temperature difference
- The heating power of 0.05 to 0.16 W and 0.4 to 1.7 W for coil 1 and 2, respectively
- Removal of offset temperature from thermal voltage of signal wires before heating

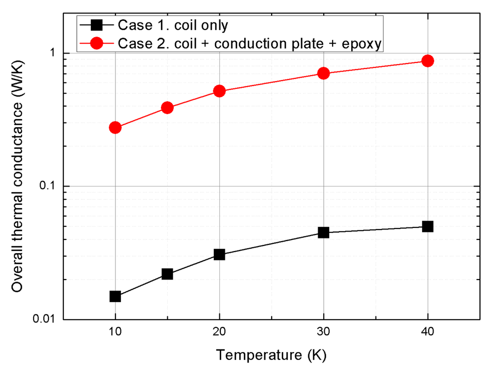
Experimental Results

- Definition of overall thermal conductance:

$$S = \frac{\dot{Q}}{\Delta T}[\mathrm{W/K}]$$

$\dot{Q}$: applied heating

ΔT: temperature difference (95 turn – 5 turn)

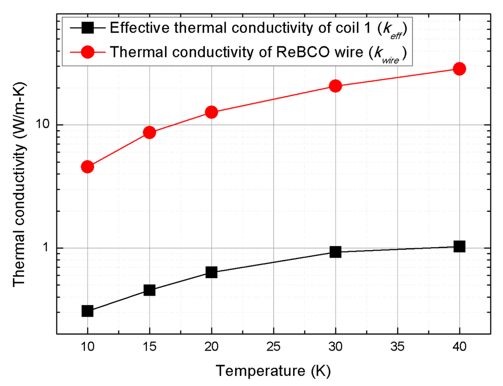


Measured overall thermal conductance of coil 1 and coil 2

- About 10 time larger overall thermal conductance of coil 2 than that of coil 1 due to the additional conductive plate and thin epoxy layer

Discussion

Thermal contact resistance



Effective thermal conductivity of coil 1 and that of ReBCO wire

$$\dot{Q} = S\Delta T = \frac{\Delta T}{R_{total}}$$

$$= \frac{\Delta T}{\ln(r_o/r_i)/(2\pi k_{eff} L)}[\mathrm{W}]$$

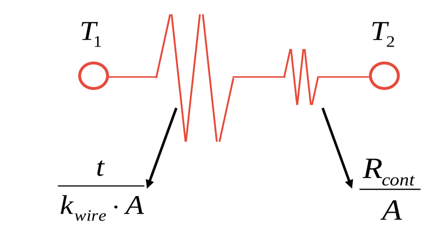
$$k_{eff} = \frac{1}{\ln(r_o/r_i)/(2\pi L S)}[\mathrm{W/m\cdot K}]$$

- 10 times smaller effective thermal conductance of wire (k_{eff}) previously reported transversal thermal conductivity of wire (k_{eff})
- → Additional TCR between winding turns as shown in thermal resistance circuit

$$R_{total} = \frac{t}{k_{eff}\cdot A} = \frac{t}{k_{wire}\cdot A} + \frac{R_{cont}}{A}[\mathrm{K/W}]$$

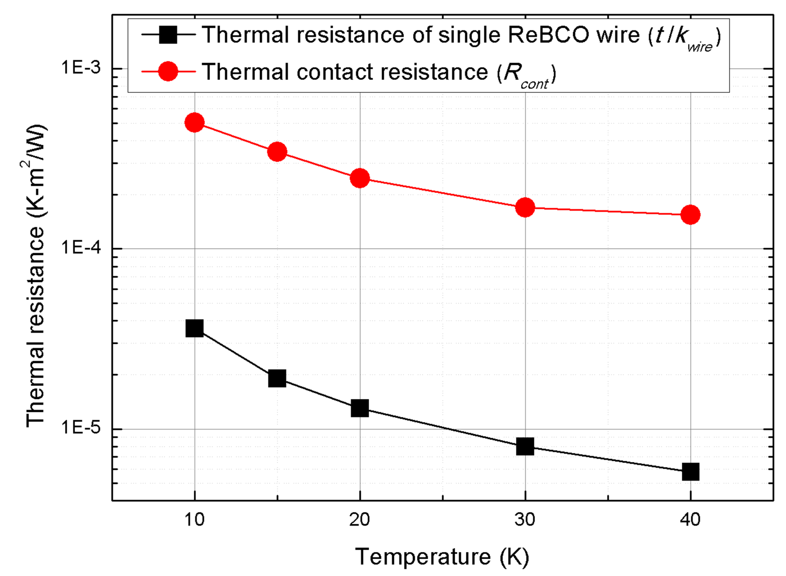
$$\frac{t}{k_{eff}} = \frac{t}{k_{wire}} + R_{cont}[\mathrm{K\cdot m^2/W}]$$

$$R_{cont} = \frac{t}{k_{eff}} - \frac{t}{k_{wire}}[\mathrm{K\cdot m^2/W}]$$



Thermal resistance circuit diagram with thermal contact resistance for single ReBCO wire

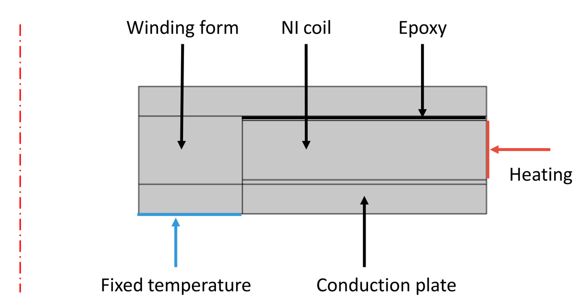
- Difference of thermal resistance of coil and wire → Thermal contact resistance



Thermal resistance of single ReBCO wire (t/k_{wire}) and thermal contact resistance (R_{cont}) of coil 1

Application of thermal contact resistance

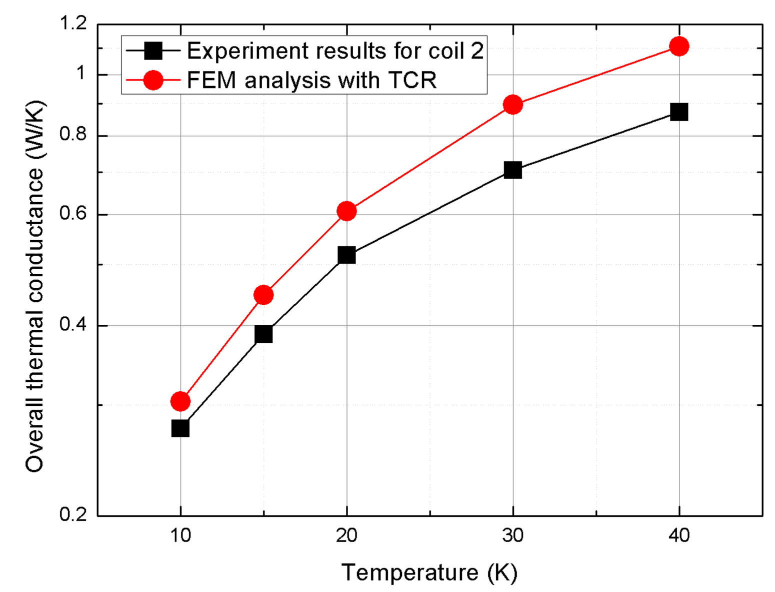
- Much enhanced the overall thermal conductance of coil 1 by conduction plate and epoxy layer
- Application of TCR for the thermal modeling of coil 2 to get the enhanced overall thermal conductance by FEM (Finite Element Method)



FEM analysis model for coil 2

- Axisymmetric thermal analysis model of coil 1 composed of conduction plates and epoxy layers
- Use known temperature dependent thermal conductivity for the metallic structure and epoxy layer
- Analysis with same heating power of temperature conditions as in the experiment.

- Using the measured TCR, it was possible to predict overall thermal conductance of coil 2 in an accuracy within 20 % error.



Comparison of overall thermal conductance by experiment and FEM analysis including TCR

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