TUE-PO1-722-02

A study on the electrical contact resistance and thermal conductivity of soldered-metal insulation coil with conduction cooling

Nov. 15-19, 2021
Fukuoka, Japan

Jaehwan Lee[1], Jeongmin Mun[2], Junil Kim[3], Kideok Sim[4], Seungyong Hahn[5], and Seokho Kim[1,*]

[1]Department of Smart Manufacturing Engineering, Changwon National University, Changwon, Gyeongsangnam-do 51140, South Korea
[2]Department Mechanical Engineering, Changwon National University, Changwon, Gyeongsang-nam-do 51140, South Korea
[3]Korea Electrotechnology Research Institute, Changwon, Gyeongsang-nam-do 51543, South Korea
[4]Supergenics, co., Ltd., Changwon, Gyeongsang-nam-do 51542, South Korea
[5]Department of Electrical and Computer Engineering, Seoul National University, Seoul 08826, South Korea

Introduction

- No-insulation (NI) winding method has been widely used in the fabrication of superconducting coils due to its excellent thermal stability and mechanical stiffness.
- In the NI coil, there is a charging delay and heat loss due to leakage current, and the metal insulated (MI) winding method has been proposed to reduce the charging delay and the heat loss by the leakage current due to the increased contact resistance by the metal tape.
- However, it is difficult to quantify the contact resistance between turns of the coil at the design stage. To resolve this problem, a new winding method named as SMI (Soldered Metal Insulation) was proposed by the authors, the electrical properties were evaluated in the bath of liquid nitrogen.
- The conducted in a conduction cooling test apparatus to investigate electrical and electric contact resistances are evaluated through sudden discharging experiments.
- Then, the thermal contact resistances are also measured using a heater installed on the outer turn of the coil.
- It is believed that the SMI winding technique can be applied to fabricate REBCO coils with predictable contact resistance.

Test coil

- A test coil was fabricated to investigate electrical/thermal characteristics of the SMI coil.
- Table Ⅰ lists the specifications of the test coil.
- The thickness of the tinned REBCO wire and STS metal insulator used in fabricating the test coils were 5μm.

Table Ⅰ. Specifications of the test coil

Parameter	Unit	Value		
Pre-tinned REBCO wire				
Overall width; thickness	mm		4.0; 0.147	
Thickness of substrate	μm		100	
Thickness of copper lamination	μm		20	
Thickness of plated Sn	μm		5	
Critical current @77 K safe-field	A		230	
Pre-tinned stainless steel tape				
Overall width; thickness	mm		4.0; 0.1	
Test coil		NI	MI	SMI
Coil I.D.; O.D.	mm	80; 94.7	80; 104.7	80; 108.7
Turns, N_t		50	50	50
Inductance, L_{coil}	μH	418.15	388.63	381.3
Magnet constant	G/A	7.178	6.81	6.67
Winding tension (HTS; STS)	kgf	2, 3.8	2; 3	2; 3

Experiment set-up

- The electrical/thermal characteristics of the test coil was investigated below 77 K using a conduction cooling test apparatus.
- A Hall sensor (Lakeshore model HGCT-3020) was installed at the center of the test coil to measure the magnetic field.
- A power supply (Cryomagnetics model 4G Four Quadrant Superconducting Magnet Power Supply) was used to control current.
- The voltage was measured using a measuring instrument (NATIONAL INSTRUMENT model NI SCXI-1000).
- A temperature sensor (LakeShore, Cernox-SD) was installed at the first and last turns of the test coil to measure the temperature difference.

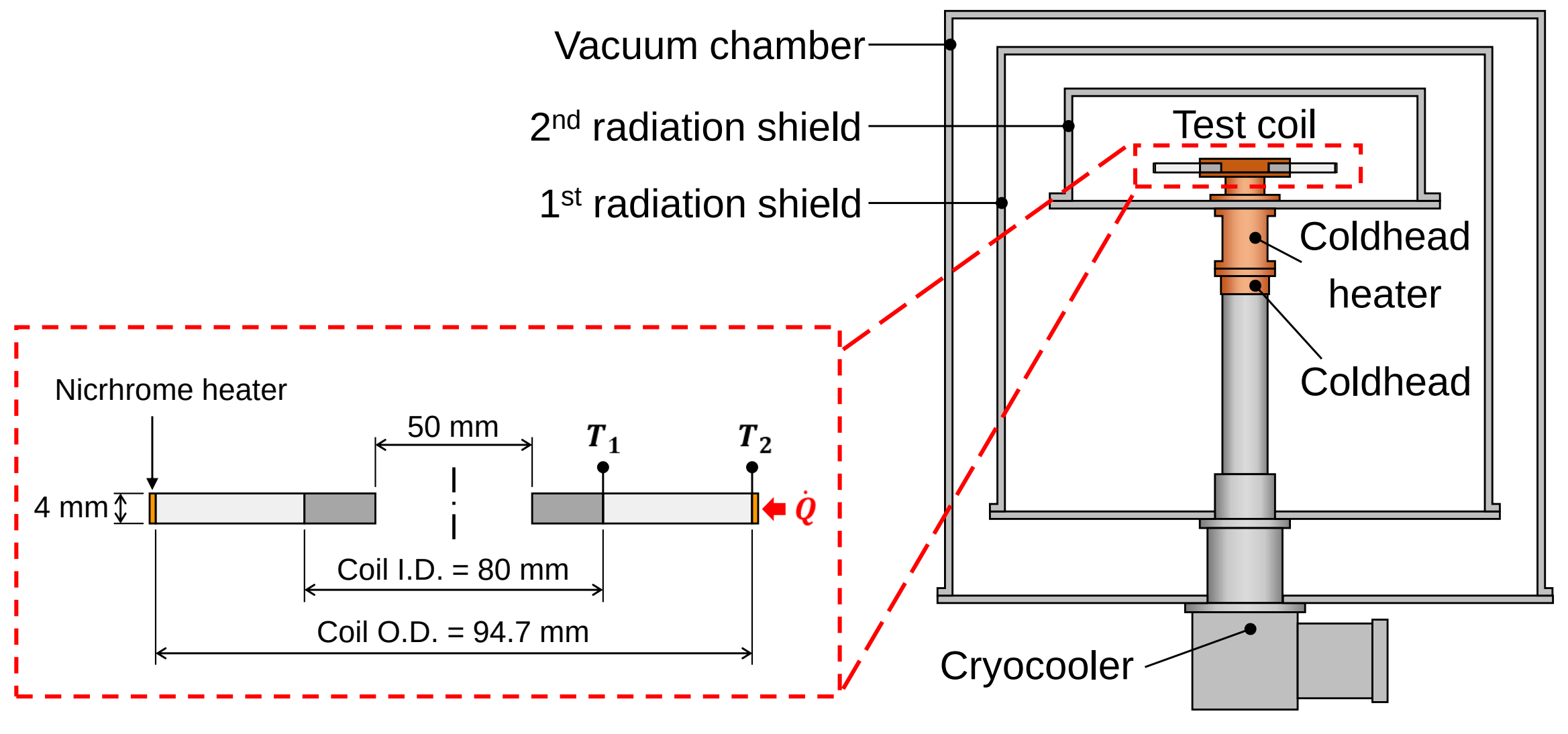
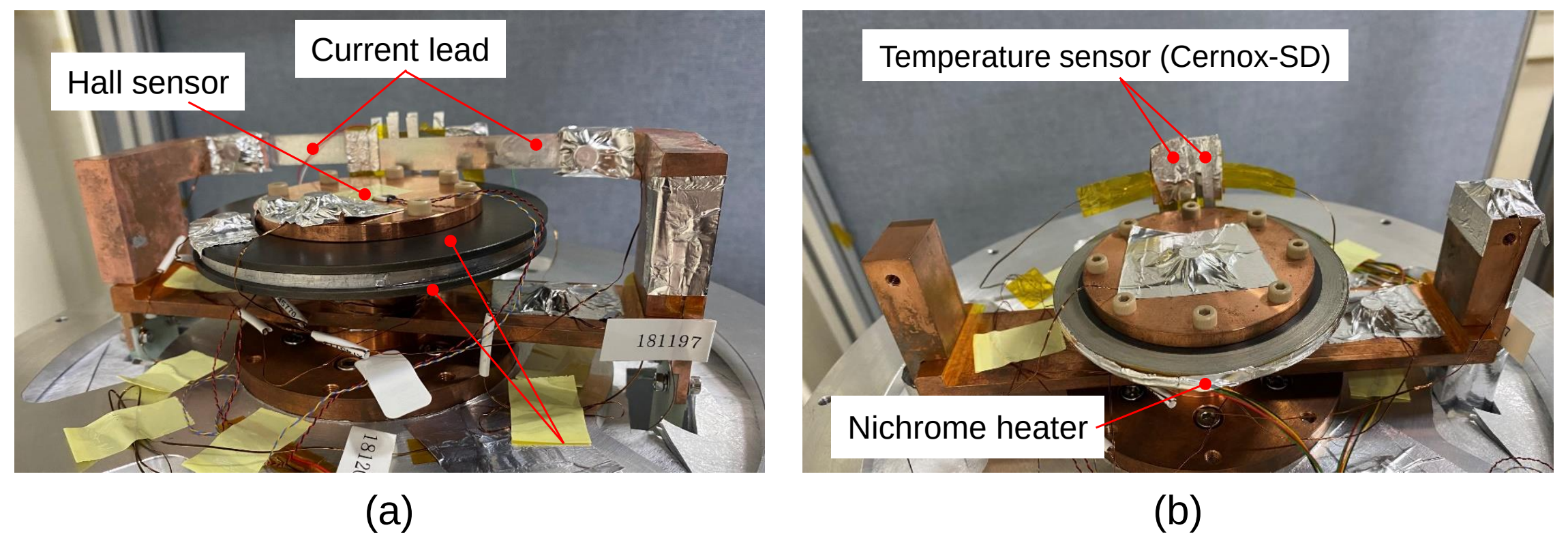


Fig. 1. Schematic of thermal conductivity measurement



(a) (b)

Fig. 2. Test coil set-up (a) electrical contact resistance measurement (b) thermal conductivity measurement

Electrical contact resistance

- A sudden discharge test was performed to measure the time constant and the contact resistance of the test coils.
- The coil was charged up to 50 A at a ramping rate of 0.1 A/s. Then, the circuit switch was opened for sudden discharge.

$$\tau = \frac{L_{coil}}{R_{eq}}$$

τ Time constant
R_{eq} Equivalent resistance
L_{coil} Coil inductance

$$R_{eq} = \sum_{i=1}^{N_t-1} \frac{R_{ct}}{2\pi r_i w_d}$$

τ Time constant
R_{eq} Equivalent resistance
R_{ct} Contact resistance
N_t No. of winding turns
r_i Winding radius per turns
w_d width of conductor

Result of the electrical contact resistance measurement

- Fig. 2. shows the time constant according to the temperature of the test coil.
- As the operating temperature of the test coil decreases, the time constant increases.
- As the winding tension of the NI coil increases, the time constant increases, and the time constant of the SMI coil is larger after heat treatment than before heat treatment.
- Fig. 3. shows the time constant according to the equivalent contact resistance of the test coil.
- As the operating temperature of the test coil increases, the equivalent contact resistance also increases.
- As the winding tension of the NI coil increases, the equivalent contact resistance also increases.
- The SMI coil improved contact between turns after heat treatment, and the equivalent contact resistance decreased.

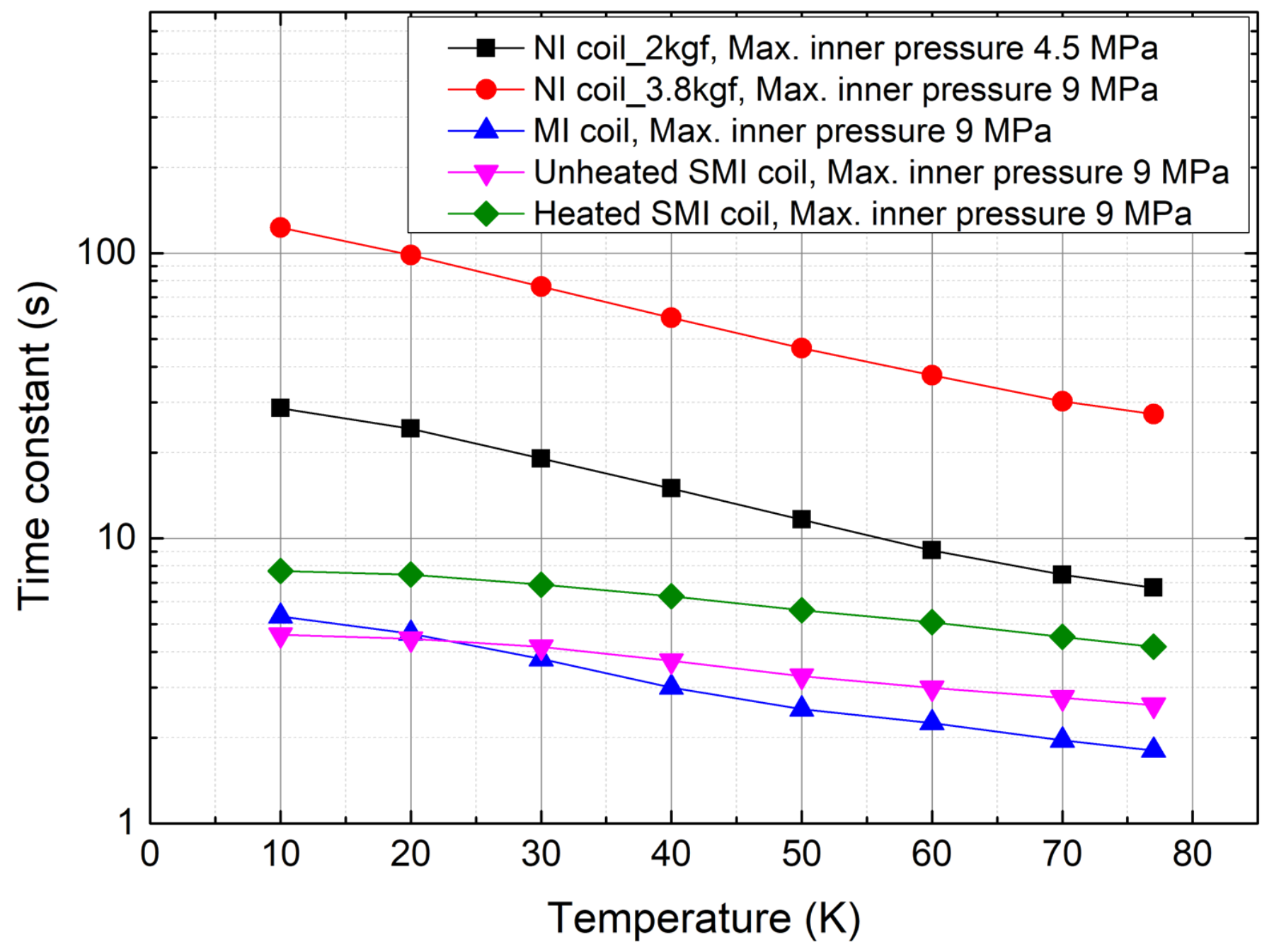


Fig. 2. Time constant according to temperature

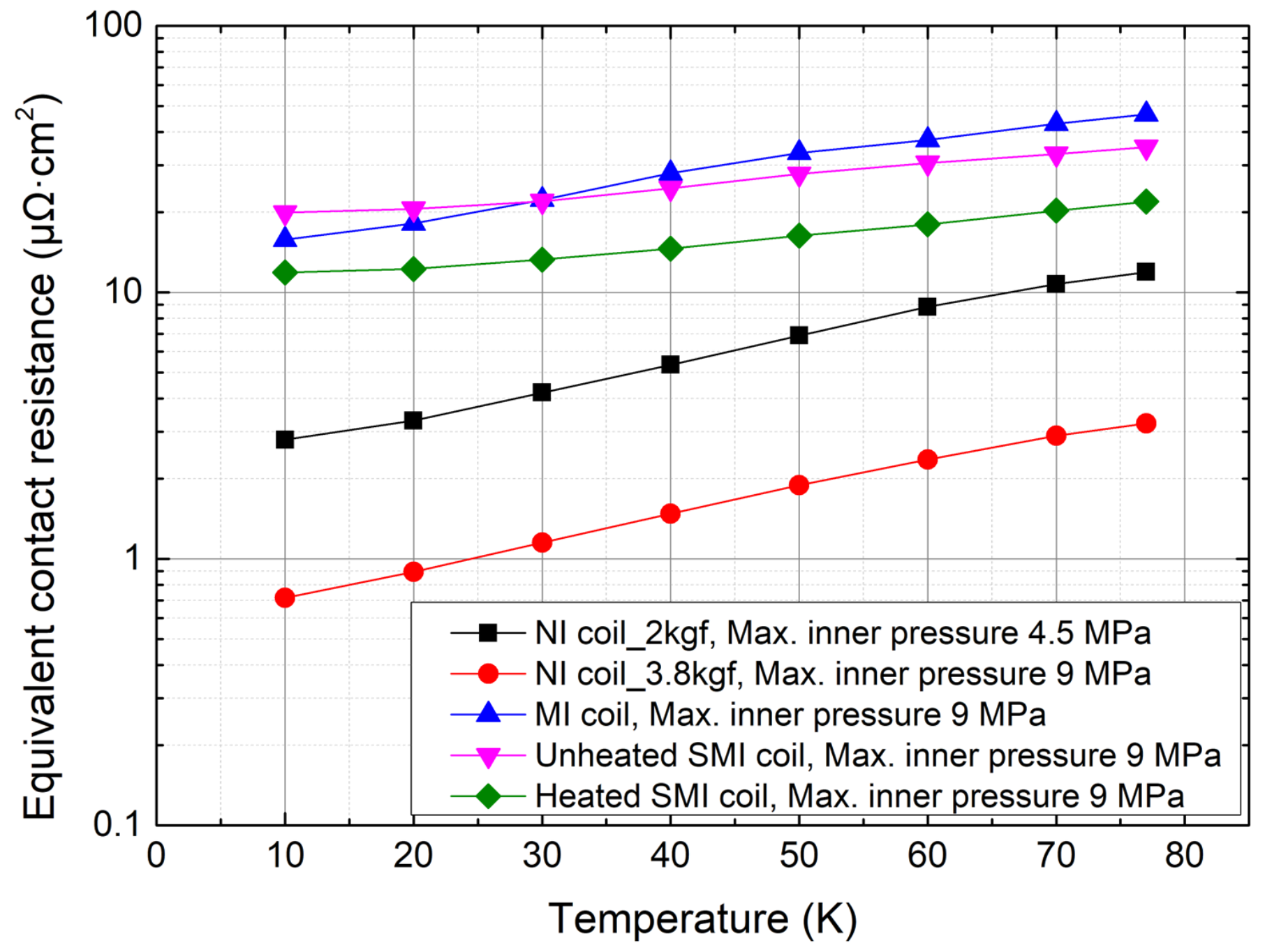


Fig. 3. Equivalent resistance according to temperature

Thermal conductivity

- To measure the thermal conductivity, the nichrome heater was installed on the last turn of the coil and a heat source was applied.
- In order to calculate the thermal conductivity of the test coil, the temperatures of the first and last coils were measured.
- Thermal conductivity was calculated using the following relational expression.

$$\dot{Q} = \frac{T_2 - T_1}{R_{\text{total}}} = 2\pi w k_{\text{eff}} \frac{T_2 - T_1}{\ln(r_0/r_\text{i})}$$

$$k_{\text{eff}} = \frac{\dot{Q}\ln(r_0/r_\text{i})}{2\pi w (T_2 - T_1)}$$

r_1 : Inner radius
r_2 : Outer radius
T_1 : Inner surface temperature
T_2 : Outer surface temperature
k_{eff} : Effective thermal conductivity
w : REBCO/SS tape width

Result of the thermal conductivity measurement

- Fig. 4. shows the Effective thermal conductivity according to temperature of the test coil.
- As the winding tension of the NI coil increases, the effective thermal conductivity increases.
- The SMI coil improved contact between turns after heat treatment, but the effective thermal conductivity decreased.
- It is estimated that the In-Sn solder increased the thermal resistance between the turns of the SMI coil.

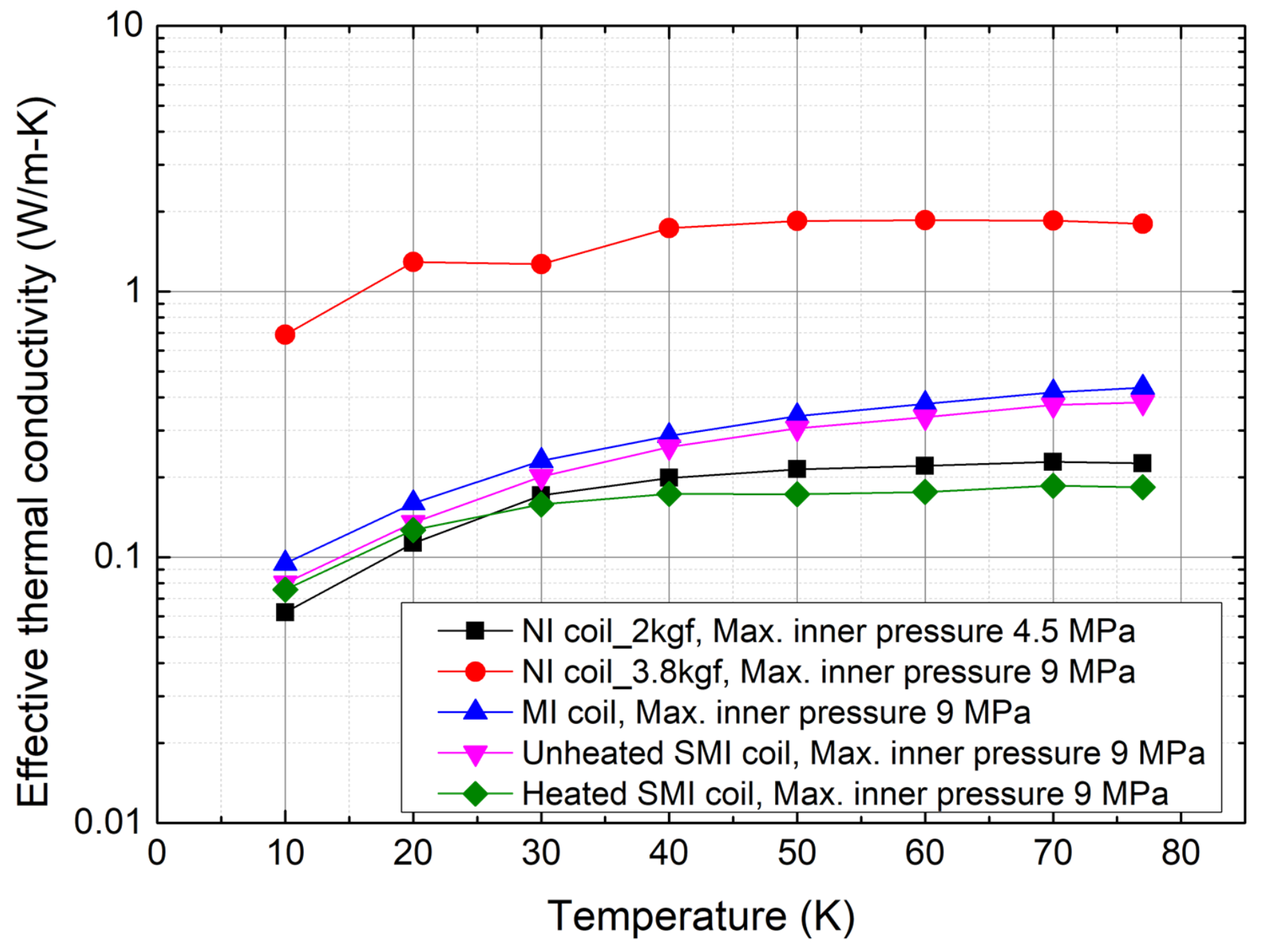


Fig. 4. Effective thermal conductivity according to temperature

Summary and Conclusion

- In this study, the electrical/thermal characteristics of the SMI coil were investigated using a conduction cooling test apparatus.
- The turn-to-turn contact of the test coil was improved by increasing the winding tension and soldering between turns, but the thermal conductivity was not improved.
- Further study is underway on the correlation between the turn-to-turn contact state of the SMI coil and the thermal conductivity.

This work was supported by the Korea Institute of National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2019R1A5A8083201) and the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, the Ministry of Food and Drug Safety) (Project Number: 202011C21)