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Development of an Optimization Program for a 2G HTS Conductor Design Process

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Abstract-- **The properties of the conductor—mechanical, thermal, and electrical—are the key information in the design and optimization of superconducting coils. Particularly, in devices using second generation (2G) high temperature superconductors (HTS), whose base materials (for example, the substrate or stabilizer) and dimensions are adjustable, a design process for conductor optimization is one of the most important factors to enhance the electrical and thermal performance of the superconducting system while reducing the cost of the conductor. Recently, we developed a numerical program that can be used for 2G HTS conductor optimization. Focusing on the five major properties, viz. the electrical resistivity, heat capacity, thermal conductivity, Z-value, and enthalpy, the program includes an electronic database of the major base materials and calculates the equivalent properties of the 2G HTS conductors using the dimensions of the base materials as the input values. In this study, the developed program is introduced and its validity is verified by comparing the experimental and simulated results obtained with several 2G HTS conductors.**

1. INTRODUCTION

In recent years, second generation (2G) high temperature superconducting (HTS) wires have gone from the laboratory stage to field tests and are now being produced with the performance required for large-scale commercial cable and coil applications. Due to their superior performance in high magnetic fields, along with the wire's light weight and high current density, 2G HTS technology has important implications for power devices such as cables, generators, motors and fault current limiters (FCLs).

In general, the 2G HTS conductor is produced as a combination of five layers; 1) substrate; 2) buffer layer; 3) superconducting layer; 4) stabilizer; and 5) reinforcement. In order for HTS coil designers to optimize their conductor for a specific HTS device, the characteristics of the conductor, such as its thermal and electrical properties, need to be obtained from the 2G HTS wire manufacturers. However, this information is very limited, since only a few years have passed since the first commercialization of YBCO 2G conductors. Even the property measurements of the "ready-made" commercial products have not been completed yet. Therefore, the estimation of the conductor properties would be quite helpful for HTS coil designers to optimize their specific conductors while saving time and effort.

In this study, we developed a numerical program for 2G conductor design optimization considering their five major properties−electrical resistivity, heat capacity, thermal conductivity, Z value and enthalpy. Using an electronic database of the major base materials of 2G conductors, the program estimates the equivalent properties of the 2G composite conductor using the dimensions of each component as the input. Also, the validity of the program is verified by comparing the experimental and estimated results of the electrical resistivity for several 2G conductors.

2. ELECTRONIC DATABASE

Fig. 1 shows a list of the properties of the five major base material used for the design and construction of the HTS coils. They are categorized into two classes; 1) the electrical properties; 2) the thermal properties. Both the electrical and thermal properties are related mostly to stability and protection issues [1, 2].

Fig. 2 shows a flow diagram of the computer code called "Equivalence V2.1", which consists of three steps, 1) the construction of the database for the major materials; 2) the calculation of the five major properties using an equivalent model for each property; 3) 2G conductor optimization for the design process. This study focused on the twenty eight materials listed in Table 1 [3]. To provide a more user-friendly interface, four subcategories were created in the database of Equivalence V2.1: 1) superconductors; 2) stabilizers and protection materials; 3) substrates and mechanical reinforcement materials; 4) solder and other base materials. The three major properties of each material, viz. their electrical resistivity, heat capacity, and thermal conductivity, were investigated in the temperature range of 1 K and 300 K. With these measured properties, the Z value and enthalpy were calculated by equations (1) and (2), respectively.

$$Z(T_1,T_2)=\int_{T_1}^{T_2}\frac{C_p(T)}{\rho(T)}dT \quad (1)$$

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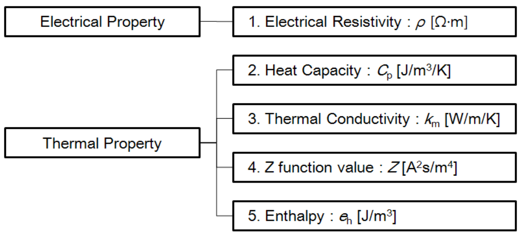


Fig. 1. Five major properties of HTS 2G conductors.

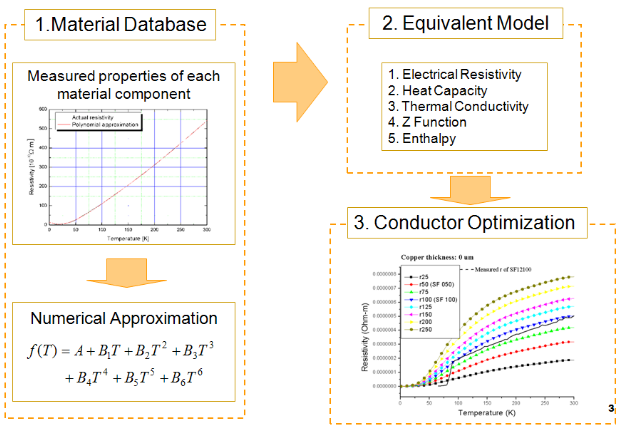


Fig. 2. "Equivalence V2.1" program flowchart.

TABLE I
DATABASE IN "EQUIVALENCE V2.1".

Material Type	Material ID	Base Material
Superconductor	1001	YBCO
	1002	NbTi alloy
	1003	Nb_3Sn
Stabilizer and Protection Material	2001	Copper (RRR50)
	2002	Copper (RRR100)
	2003	Copper (RRR200)
	2004	Silver
	2005	Aluminum (RRR50)
	2006	Aluminum (RRR100)
	2007	Aluminum (RRR200)
	2008	Gold
Substrate and Mechanical Reinforcement Material	3001	Nickel
	3002	Stainless steel
	3003	Hastelloy C276
	3004	Titanium
	3005	Cu-Ni 9010
	3006	Cu-Ni 7030
	3007	Annealed Inconel 718
	3008	Cold-worked Inconel 718
	3009	Steel 4340
Solder and Other Base Material	4001	Indium
	4002	Lead
	4003	Beryllium
	4004	Niobium
	4005	PbSn
	4006	Manganin
	4007	Constantan
	4008	Beryllium Copper
	4009	Phosphor Bronze

$$e(T_1,T_2) = \int_{T_1}^{T_2} C_p(T)dT \tag{2}$$

where C_p and ρ are the heat capacity and electrical resistivity, respectively.

3. OPTIMIZATION WITH EQUIVALENT MODEL

Fig. 3 shows a schematic drawing of a composite YBCO coated conductor composed of four different base materials used for the equivalent model of the electrical resistivity, heat capacity and thermal conductivity. In this study, only the longitudinal properties (z direction in Fig. 3) of the electrical resistivity and thermal conductivity are calculated by the equivalent models. Both the transverse (x direction in Fig. 3) and perpendicular (y direction in Fig. 3) properties can be neglected in the design of an HTS coil, because the normal zone propagation velocity (NZPV) of an HTS in the temperature range of 60 K and 70 K (HTS power device operating temperature range) is very low (< 1 mm/s), due to the insulation in these directions [4, 5]. Exceptions include the heat capacity, which is a scalar variable.

3.1. Electrical Resistivity

The equivalent electrical resistivity can be calculated using equations (3) and (4).

$$V = I_1\rho_1\frac{L}{S_1} = I_2\rho_2\frac{L}{S_2} = I_3\rho_3\frac{L}{S_3} = I_4\rho_4\frac{L}{S_4} = (I_1+I_2+I_3+I_4)\rho_{eq}\frac{L}{(S_1+S_2+S_3+S_4)} \tag{3}$$

$$\rho_{eq} = \frac{(S_1+S_2+S_3+S_4)}{\left(\frac{S_1}{\rho_1}+\frac{S_2}{\rho_2}+\frac{S_3}{\rho_3}+\frac{S_4}{\rho_4}\right)} \tag{4}$$

where ρ_i, S_i, and I_i are the i-th conductor's cross-section area, resistivity, and current, respectively; L is the sample length in the z-direction and V is the voltage across the sample.

A general expression for the longitudinal component of the electrical resistivity in composite YBCO 2G conductors is as follows.

$$\rho_{eq} = \frac{\sum_{i=1}^{n} S_i}{\sum_{i=1}^{n}\left(\frac{S_i}{\rho_i}\right)} \tag{5}$$

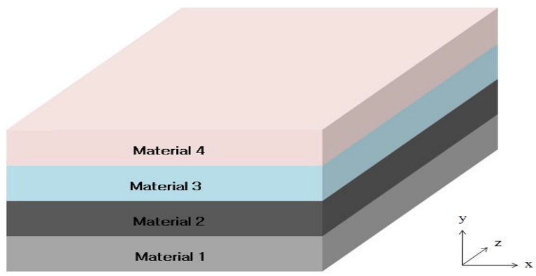


Fig. 3. Schematic drawing for the equivalent model study.

3.2. Heat Capacity

The equivalent heat capacity, C_{peq}, of the four-composite conductor can be calculated using equations (6) ~ (8).

$$Q_i = C_{pi} S_i L \Delta T \tag{6}$$

$$Q = Q_1 + Q_2 + Q_3 + Q_4 = C_{peq}(S_1 + S_2 + S_3 + S_4) L \Delta T \tag{7}$$

$$C_{peq} = \frac{(C_{p1}S_1 + C_{p2}S_2 + C_{p3}S_3 + C_{p4}S_4)}{(S_1 + S_2 + S_3 + S_4)} \tag{8}$$

where Q_i, C_{pi}, and S_i are the i-th component's heat input, heat capacity, and cross-section area , respectively.

A general expression for the equivalent heat capacity in a composite YBCO 2G conductor is as follows.

$$C_{peq} = \frac{\sum_{i=1}^{n}(C_{pi}S_i)}{\sum_{i=1}^{n}(S_i)} \tag{9}$$

3.3. Thermal Conductivity

The equivalent thermal conductivity can be calculated using equations (10) and (11), regardless of the relative positions of the base material components.

$$\Delta T = q_{z1}\frac{L}{k_{m1}S_1} = q_{z2}\frac{L}{k_{m2}S_2} = q_{z3}\frac{L}{k_{m3}S_3} = q_{z4}\frac{L}{k_{m4}S_4} = (q_{z1} + q_{z2} + q_{z3} + q_{z4})\frac{L}{k_{meq}(S_1 + S_2 + S_3 + S_4)} \tag{10}$$

$$k_{meq} = \frac{\sum_{i=1}^{n}(K_{mi}S_i)}{\sum_{i=1}^{n}(S_i)} \tag{11}$$

where k_{mi}, S_i, and q_{zi} are the i-th conductor's thermal conductivity, cross-section area, and heat flow, respectively; L is the sample length in the z-direction and ΔT is the temperature difference across the sample.

A general expression for the longitudinal component of the thermal conductivity in composite YBCO 2G conductors is as follows.

$$k_{meq} = \frac{\sum_{i=1}^{n}(K_{mi}S_i)}{\sum_{i=1}^{n}(S_i)} \tag{12}$$

4. CASE STUDY AND DISCUSSION

In this study, as conductor design examples, the equivalent properties of SuperPower SF12100 and SCS4050 conductors are simulated using Equivalence V2.1. Also, the simulated results of the electrical resistivity for these two conductors are compared with the actual measurements.

4.1. Simulation for SF12100

Fig. 4 shows the major components and thickness of each component of SuperPower SF12100. Overall, it is composed of a Hastelloy C276 substrate and silver (Ag) overlayer with thicknesses of 0.1 mm and 0.002 mm, respectively. The thickness of the stabilizer is negligible, because SF12100 is a stabilizer free conductor [6]. The simulation and experimental results of the electrical resistivity are compared in Fig. 5. In the experimental results, there is a normal to superconductor phase transition at around 90 K, which is the critical temperature of YBCO. The simulation results agreed well with the experimental measurements, which demonstrates the validity of the developed code.

4.2. Simulation for SCS4050

Fig. 6 shows the major components and thickness of each component of SuperPower SCS4050. In general, it is composed of a Hastelloy C276 substrate, copper (Cu) RRR 100 stabilizer and Ag overlayer with thicknesses of 0.05 mm, 0.04 mm and 0.002 mm, respectively [6]. The simulation and experimental results of the electrical resistivity are compared in Fig. 7. As in the case of SF12100, a normal to superconductor phase transition is observed at around 90 K. Again, the results from the simulation are in good agreement with those from the experiments after the range of the critical temperature, which demonstrates the validity of the developed code.

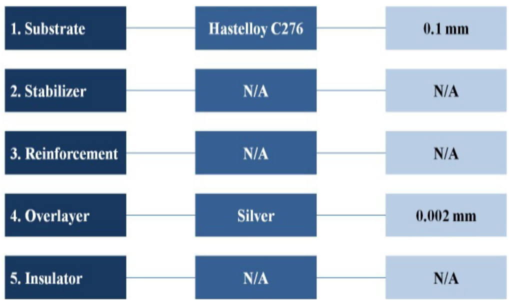


Fig. 4. Major components and thickness of each component in the conductor design study using SuperPower SF12100 with a conductor width of 12 mm [6].

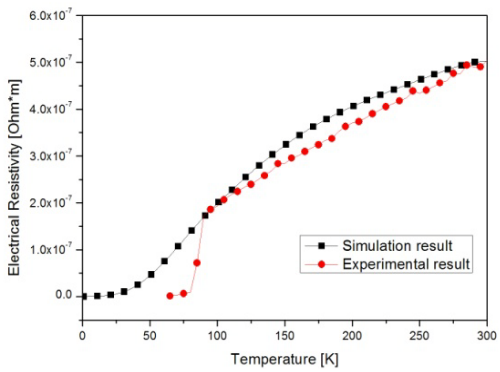


Fig. 5. Simulation and experimental results of electrical resistivity for SF12100.

Fig. 6. Major components and thickness of each component in the conductor design study using SuperPower SCS4050 with a conductor width of 4 mm [6].

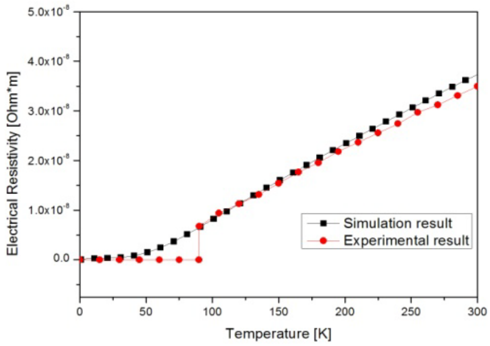
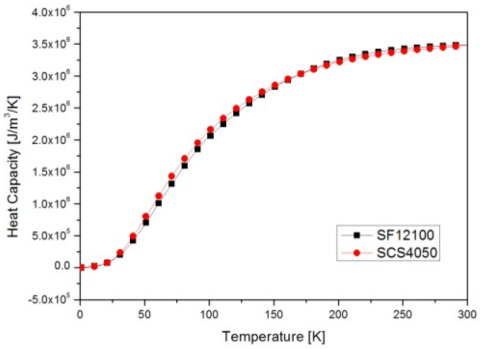


Fig. 7. Simulation and experimental results of electrical resistivity for SCS4050.

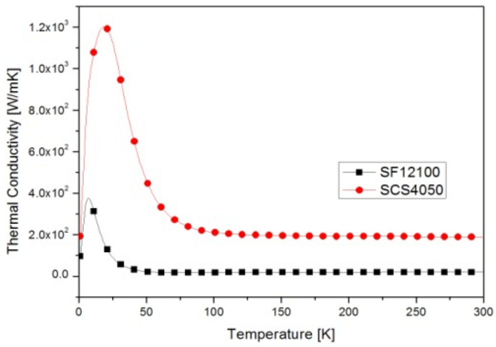
Figs. 8 shows the simulation results of the heat capacity, thermal conductivity, Z value and enthalpy for SF12100 and SCS4050. Due to the limited information available on the major properties of the various base materials, it is currently impossible to compare the simulation and experimental results . However, it can be inferred from the comparative analysis of the equivalent electrical resistivity that the simulation results match well with the actual measurements for these values.

5. CONCLUSION

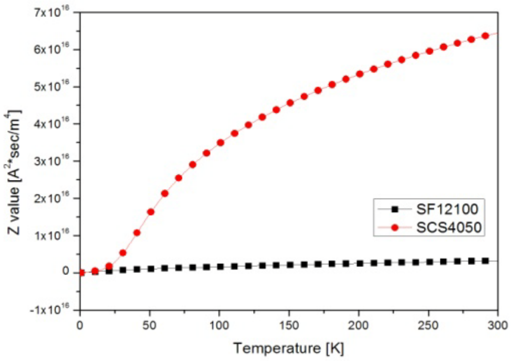
In this study, we developed a numerical program, Equivalence V2.1, that includes an electronic database of most of the base materials used for 2G HTS conductors in the temperature range of 1 K and 300 K. Based on the five major properties of the conductors, viz. the electrical resistivity, heat capacity, thermal conductivity, Z value and enthalpy, this program estimates the equivalent properties of various 2G composite conductors using the dimensions of each component as the input values. The simulation results of the electrical resistivity are in good agreement with the experimental measurements for these two commercial 2G conductors. Therefore, the validity of the developed program is demonstrated. In the future, we will continue the verification of Equivalence V2.1 through the experimental measurement of the heat capacity, thermal conductivity, Z value and enthalpy of various 2G HTS conductors.



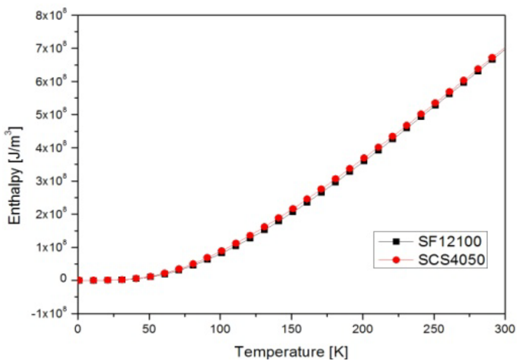
(a)



(b)



(c)



(d)

Fig. 8. Simulation results of major properties for SF12100 and SCS4050: (a) Heat capacity; (b) Thermal conductivity; (c) Z value; (d) Enthalpy.

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