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A comparison on the heat load of HTS current leads with respect to uniform and non-uniform cross-sectional areas

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Abstract

Current lead is a device that connects the power supply and superconducting magnets. High temperature superconductor (HTS) has lower thermal conductivity and higher current density than normal metal. For these reasons, the heat load can be reduced by replacing the normal metal of the current lead with the HTS. Conventional HTS current lead has same cross-sectional area in the axial direction. However, this is over-designed at the cold-end (4.2 K) in terms of current. The heat load can be reduced by reducing this part because the heat load is proportional to the cross-sectional area. Therefore, in this paper, heat load was calculated from the heat diffusion equation of HTS current leads with uniform and non-uniform cross-sectional areas. The cross-sectional area of the warm-end (65K) is designed considering burnout time when cooling system failure occurs. In cold-end, Joule heat and heat load due to current conduction occurs at the same time, so the cross-sectional area where the sum of the two heat is minimum is obtained. As a result of simulation, current leads for KSTAR TF coils with uniform and non-uniform cross-sectional areas were designed, and it was confirmed that the non-uniform cross-sectional areas could further reduce the heat load.

Keywords: HTS current lead, heat load, thermal conductivity, non-uniform cross-sectional areas, KSTAR TF coil

1. INTRODUCTION

The current lead is a device for connecting tokamak system and accelerator between the liquid helium and a power supply at room temperature to transport current [1]. The conventional current lead is manufactured by normal metal which has the disadvantage that the heat input from the outside to the tokamak system is large. In order to overcome this disadvantage, the heat load can be reduced by using HTS that has zero resistance and low thermal conductivity at temperature below the critical temperature. The HTS current lead consists of a heat exchanger (HEX) from 300 K to 65 K and an HTS module from warm-end (65 K) to cold-end (4.2 K) [2].

The HTS module consists of a shunt and HTS stacks. Shunt protects the HTS module by bypassing the current that was energized by the HTS stacks in case of an accident and supports the HTS stacks. HTS stacks conduct high current under operating condition and Joule heat does not occur due to zero resistance characteristic below the critical temperature. Therefore, shunt and HTS stacks are important to minimize the heat load into cold-end at warm-end. The conventional HTS module has the same cross-sectional area in the axial direction (from warm-end to cold-end) of both shunt and HTS stacks. The uniform structure is inefficient in thermal properties because the heat load is proportional to the size of the cross-sectional area.

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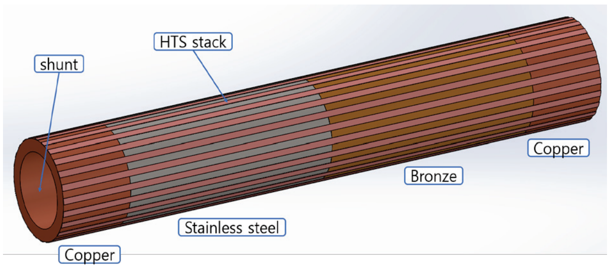

Fig. 1. HTS module consisting of shunt and HTS stacks.

In this paper, a non-uniform HTS module was designed with different cross-sectional areas from warm-end to cold-end to reduce the heat load. The heat load was compared with the conventional uniform HTS module through simulation. The heat input to the magnet environment at cold-end by an HTS module is ideally by conduction as follows [3]

$$Q = k(z,T)A(z)\frac{dT}{dz} \tag{1}$$

where, $k(z,T)$ and $A(z)$ are the thermal conductivity according to position and temperature, and cross-sectional area according to position of HTS module, respectively.

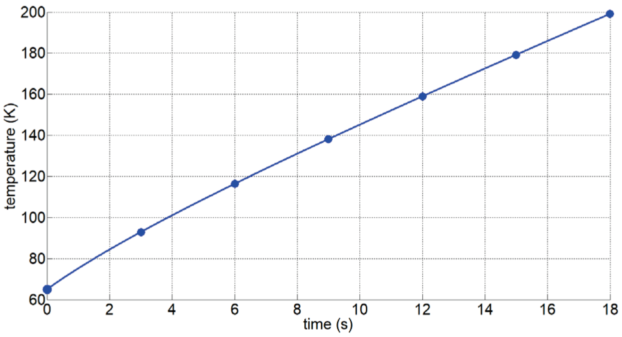

Fig. 2. Temperature at warm-end when cooling system failure occurs.

2. DESIGN OF SHUNT

2.1. Cross-sectional Area at Warm-end

The current lead is cooled by vapor cooling with the liquid helium at the cold-end. Therefore, the bronze is located near the warm-end of the thermally weakest shunt because of its high specific heat [4]-[6]. The HTS stack is quenched by a cooling system failure and the operating current is bypassed to the shunt. Joule heat is generated by the shunt resistance which causes flow stoppage meltdown near the warm-end. The burnout time is the time at which the temperature near the warm-end increases steadily and reaches the hot spot max temperature (200 K) [4]-[7]. It is important to increase the burnout time that the HTS module can operate reliably until the current is discharged when an accident occurs. The burnout time is proportional to the cross-sectional area and the specific heat, so the bronze was applied. The time-dependent power equation for a differential element of an optimum lead follows [3]

$$AC(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left[Ak(T)\frac{\partial T}{\partial z}\right]-\dot{m}_I c_p(T)\frac{\partial T}{\partial z}+\frac{\rho(T)}{A}I_o^2 \tag{2a}$$

at cooling system failure

$$\frac{d}{dz}\left[Ak(T)\frac{dT}{dz}\right]=0 \text{ and } \dot{m}_I c_p(T)\frac{dT}{dz}=0 \tag{2b}$$

If the Joule heat does not cool and the temperature increases, the cross-sectional area follows [3]

$$A=I_o\sqrt{\frac{\rho(T)}{c(T)\frac{dT}{dt}}} \tag{2c}$$

where, A and I_o are the cross-sectional area at the warm-end and operating current, respectively. $c(T)$ and $k(T)$ are the specific heat and the thermal conductivity according to temperature, respectively. $\dot{m}_I$ is the helium mass flow rate from cold-end to warm-end. $c_p(T)$ and $\rho(T)$ are the specific heat of helium and electrical resistivity of bronze according to temperature, respectively.

The cross-sectional area is 25 cm^2 for burnout time is 18 sec. Fig. 2 shows the temperature over time from the quench due to the cooling system failure when the cross-sectional area is 25 cm^2 at the warm-end.

2.2. Cross-sectional Area at Cold-end

The current is bypassed from HTS stack to copper at the cold end in the steady-state condition, so that Joule heat as well as heat load is generated simultaneously. As the cross-sectional area decreases, the heat load decreases but the Joule heat increases. In order to reduce the total heat generated in the cold-end, the cross-sectional area cannot be continuously increase or decrease. Therefore, the cross-sectional area at which the sum of the two heats is minimized can be obtained through the power density equation [3]

$$\frac{d}{dz}\left[Ak(T)\frac{dT}{dz}\right]-\dot{m}_I c_p(T)\frac{dT}{dz}+\frac{\rho(T)}{A}I_o^2=0 \tag{3a}$$

The high current is bypassed from the HTS stack to the copper of the shunt, so the high-current approximation is given by,

$$-\dot{m}_I c_p(T)\frac{dT}{dz}+\frac{\rho(T)}{A}I_o^2=0 \tag{3b}$$

The helium mass flow rate at cold-end is given by

$$\dot{m}_I=I_o\sqrt{\frac{k_{Cu}\rho_{Cu}}{c_{po}h_L}} \tag{3c}$$

where, k_{Cu} and ρ_{Cu} are the thermal conductivity and electrical resistivity of copper at cold-end, respectively. c_{po} and h_L are the specific heat of liquid helium at cold-end and liquid helium's latent heat of vaporization, respectively. The optimal current lead parameter ratio (ς_o) at cold-end is calculated by [3],

$$\left(\frac{I_o l_{Cu}}{A_{Cu}}\right)_{ot}\equiv\varsigma_o\cong\left[\int_{T_1}^{T_2}\frac{dT}{\rho_{Cu}(T)}\right]\sqrt{\frac{c_{pc}k_o\rho_o}{h_L}} \tag{3d}$$

where, A_{Cu} and l_{Cu} are the cross-sectional area and length of copper, respectively. T_1 and T_2 are the temperature at cold end and boundary between copper and stainless steel, respectively. The $\rho_{Cu}(T)$ is the electrical resistivity of copper according to temperature.

The cross-sectional area at cold-end is 15 cm^2. A design with a non-uniform cross-sectional area from warm-end to cold-end can reduce the heat load.

3. DESIGN OF HTS STACK

3.1. Temperature Distribution

The HTS stack does not generate Joule heat when current

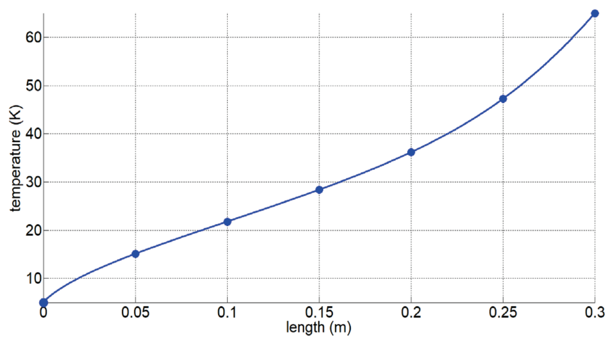

Fig. 3. Temperature distribution of the HTS stack in the axial direction.

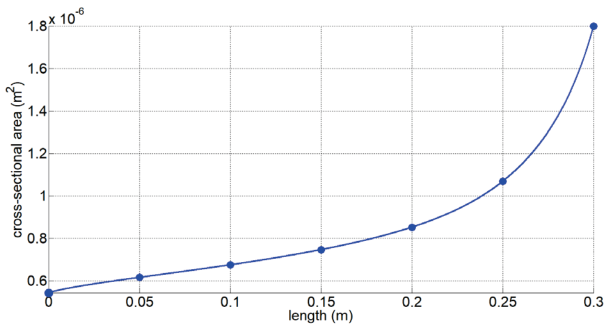

Fig. 4. Cross-sectional area of an HTS tape with a constant safety factor (S) from cold-end to warm-end.

flows in steady-state condition, but heat load is generated. It is important to reduce the size of the cross-sectional area in thermal efficiency because the heat load is proportional to the cross-sectional area. The critical current density of HTS tape varies with temperature. HTS tape has a higher critical current density at the cold-end than at the warm-end. This means that HTS tape requires a smaller cross-sectional area to has the same critical current at the cold end than at the warm end. Therefore, non-uniform HTS tape with reduced cross-sectional area from warm-end to cold-end can reduce heat load.

The heat load is proportional to the thermal conductivity. The temperature distribution is important because the thermal conductivity has a large variation with temperature.

The one-dimensional heat diffusion equation in steady state condition with no energy generation to obtain the temperature distribution is as follows [8]

$$\frac{d}{dz}\left(k(z,T)\frac{dT}{dz}\right)=0 \qquad (4)$$

where, $k(z,T)$ is the thermal conductivity of HTS tape according to position and temperature. Fig. 3 shows the temperature distribution of the HTS stack in the axial direction.

3.2. Safety Factor

The safety factor (S) is defined as the ratio of the operating current to the critical current as follows [9]

$$S=\frac{J_c(T)A}{I} \qquad (5)$$

where, $J_c(T)$ is the critical current density according to temperature (T). I and A are the operating current and cross-sectional area, respectively. The S of the cold-end is larger than the S of the warm-end in a HTS stack with a constant cross-sectional area because J_c decreases as temperature increasing. If the size of the cross-sectional area is changed so that S is constant at all positions of the HTS stack, the cross-sectional area decreases toward the cold-end. The reduced cross-sectional area reduces heat load because the heat load into the cold-end through the HTS stack is proportional to the cross-sectional area [1]. The critical current density with respect to temperature of HTS stack is as follows [3]

TABLE I
SPECIFICATION OF AN HTS TAPE.

Description	Specification
Manufacturer	SuNAM
Stabilizer	Copper
Width	12 mm
Thickness	0.15 mm
Critical current	650 A at 77 K

$$J_c(T)=J_{co}\left(\frac{T_c-T}{T_c-T_{op}}\right) \qquad (6)$$

where, J_{co} is the critical current density at T_{op} which is 77 K. T_c is the critical temperature of HTS stack. Fig. 4 show the cross-sectional area of an HTS tape with a constant safety factor from cold-end to warm-end. Table I shows the specification of an HTS tape for the calculation of critical current according to temperature. In cold-end, the same current can be transferred in cross-sectional area of 30 % compared to warm-end.

4. DESIGN OF HTS MODULE

Fig. 5 (a) shows uniform outer diameter and non-uniform inner diameter. The outer diameter must be the uniform because the HTS stack must be soldered outside the shunt. Therefore, the inner diameter of shunt is increased to reduce the cross-sectional area from warm-end to cold-end. It has a cross-sectional area of 25 cm^2 to meet the burnout time of the HTS module in the warm-end and a cross-sectional area of 15 cm^2 in the cold-end to minimize the sum of the Joule heat and heat load. Although the structure in which the cross-sectional area decreases linearly from the warm-end to the cold-end is not the optimal design, the approximate structure is presented to compare the heat load of the uniform and non-uniform structures. Fig. 5 (b) shows an HTS stack of non-uniform structure. The width at the cold-end is 3.6 mm to obtain the critical current according to the temperature of the HTS tape and to have the same S as the warm-end. As shown in Fig. 4, the cross-sectional area is non-linear but designed to be linear for ease of manufacture. Fig. 6 shows the schematic of non-uniform shunt and HTS stack. The non-uniform HTS stack soldered outside the shunt.

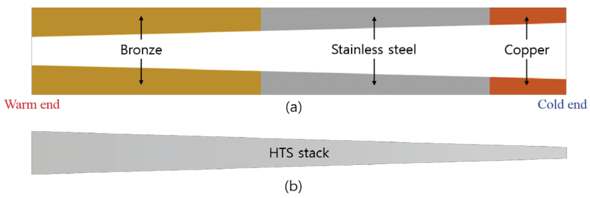

Fig. 5. Schematic of (a) internal structure of non-uniform shunt, (b) an HTS tape of non-uniform structure.

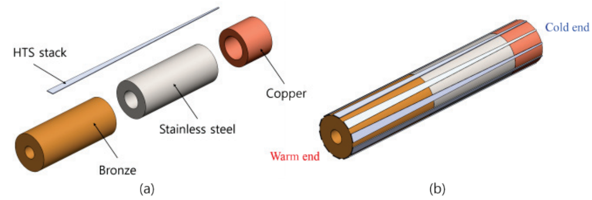

Fig. 6. Schematic of (a) separated and (b) assembled non-uniform shunt and HTS stack, respectively.

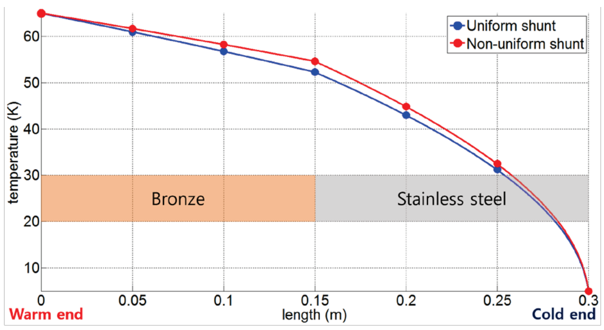

Fig. 7. Temperature distribution of shunt in the axial direction with respect to uniform and non-uniform cross-sectional areas.

5. RESULTS AND DISCUSSION

Fig. 7 shows the temperature distribution of shunt in the axial direction with respect to uniform and non-uniform structure. The temperature distribution in the axial direction is determined by the length of each material, the thermal conductivity and the size of the cross-sectional area. Therefore, non-uniform structure shunt with different cross-sectional area along the axial direction exhibits different temperature distribution [8].

The heat load is proportional to the thermal conductivity, which varies with temperature. The thermal conductivity at each position changes because the temperature distribution depends on the shunt structure. Therefore, the temperature distribution of the shunt is important to obtain the heat load that inflow in the cold-end by the shunt.

Copper of cold-end was fixed to a length of 5 *cm* to solder the HTS stacks, and the heat load according to the length of the binary shunt consisting of stainless steel and bronze was obtained. The 35 kA HTS module considering the critical current margin of about 40% [5], [6] requires 50 HTS tapes with a width of 12 *mm* and a thickness of 0.15 *mm*. Fig.7 shows the heat load according to length of HTS module

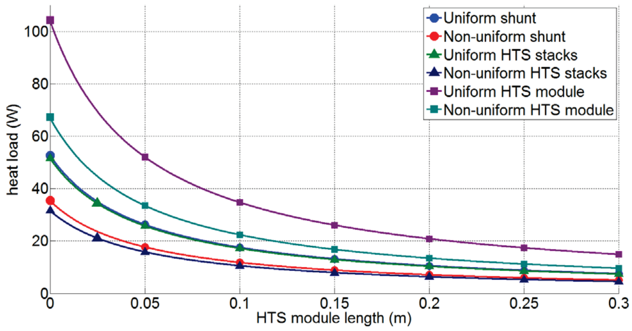

Fig. 8. The heat load according to length of HTS module with respect to uniform and non-uniform structure.

TABLE II
HEAT LOAD OF EACH STRUCTURE.

Description	Uniform shunt	Non-uniform shunt	Uniform HTS stacks	Non-uniform HTS stacks	Uniform HTS module	Non-uniform HTS module
Heat load [W]	7.53	5.07	7.37	4.52	14.89	9.59

with respect to uniform and non-uniform structure. The uniform HTS module is consist of shunt and HTS stacks of uniform structure. The non-uniform HTS module is consist of shunt and HTS stacks of non-uniform structure. The heat load of 30 *cm* long uniform and non-uniform HTS module are 14.89 and 9.59 W as shown in Table II, respectively. As a result, it was confirmed that the heat load was reduced in the non-uniform HTS module.

6. CONCLUSION

This study was performed to reduce the heat load from warm-end to cold-end of the HTS module. The cross-sectional area of the shunt at the warm-end must be determined to meet the burn time, which is the time to reach the hot spot max temperature when cooling system failure occurs. In the cold-end, the cross-sectional area of the shunt at which the sum of heat load and Joule heat is minimized must be obtained. HTS tape increases the critical current density with decreasing temperature, so it can reduce the heat load by reducing the cross-sectional area from warm-end to cold-end. The heat load of the non-uniform HTS module obtained in this study has thermal stability compared to the uniform HTS module. It is shown that the heat load decreases in the non-uniform HTS module.

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