ANALYSIS ON VAPOR COOLED CURRENT LEAD STRUCTURES FOR THE SUPERKEKB IR SC CORRECTION COILS

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Abstract

To energize the 40 superconducting (SC) correction coils of 50 A in the SuperKEKB interaction region (IR) magnet system, a compact 8-lead unit with two vapour cooled current lead structures is proposed. The theoretical derivation and solution of the general thermal balance equation based on one dimensional lead model are introduced in this paper. A numerical integration method to estimate the material optimum shape factor is presented, in which three materials are investigated for our R&D. Two structures are designed and their thermal and flow conditions are theoretically analyzed in this paper. The value of the heat transfer efficiency between helium and lead assumes minimum at the cold end and is calculated at 5 K for a conservative estimate. The influence on the heat leak to the cold end will be discussed.

INTRODUCTION

In the proposed SuperKEKB interaction region (IR) magnet system 40 superconducting (SC) correction coils are designed to perform some specific functions with current of about 50 A [1]. To energize these coils, 80 current leads will be mounted in the cryostats where the stringent spatial constraint and the cryogenic operation require a compact and optimum design. We propose a compact unit to integrate 8 helium vapour cooled leads (4 pairs). The 8 leads are made of brass with copper content of 90 % and consist of two structures for the transported current and helium vapour. The structures are designed with the theoretical analysis and finite element model (FEM). This paper will introduce the theoretical design of the geometry, analysis on the thermal and flow conditions and estimation on heat leak to the cold end.

GENERAL EQUATION AND SOLUTION

The current lead heat input is comprised of two sources: thermal conduction and Joule heating. The heat leak to lead cold end will be absorbed by the vaporization latent heat of some liquid helium (LHe). The sensible heat of the vapour up to room temperature is about 70 times larger and can fully be utilized by vapour cooled current lead. The one-dimensional theoretical treatment for the conductor and helium vapour, shown in Fig. 1, is followed by most of the researchers [2]. The thermal equilibrium for an element δx is given as

$$k(\theta)A\left.\frac{d\theta}{dx}\right|_{x+\delta x}-k(\theta)A\left.\frac{d\theta}{dx}\right|_{x}-H+\frac{I^2\rho(\theta)dx}{A}=0 \quad (1)$$

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where A is the cross-sectional area and H is the rate of heat transfer to the coolant. The equation can be solved with making assumption that the lead and vapour are both at the same temperature at any longitudinal point along lead. By defining an heat transfer efficiency *f*, the H can be substituted by $H=f\dot{m}C_p\delta\theta$, where C_p is the gas specific heat. Eq. 1 becomes

$$\frac{d}{dx}\left(k(\theta)A\frac{d\theta}{dx}\right)-f\dot{m}Cp\frac{d\theta}{dx}+\frac{I^2\rho(\theta)}{A}=0 \quad (2)$$

The thermal conductivity $k(\theta)$ and electrical resistivity $\rho(\theta)$ of most metals and alloys are inversely related, as it is shown by the Wiedemann-Franz Law,

$$k(\theta)\rho(\theta)=L_0\theta \quad (3)$$

where L_0 is the Lorenz number, 2.45×10^{-8} WΩ/K^2. It is impossible to minimize both the first term and the third of Eq. 2 simultaneously and the minimum heat leak does exist with the optimum design. The nonlinear term in Eq. 2 can be linearized by the following substitution

$$dz=\frac{Idx}{k(\theta)A} \quad (4)$$

With the boundary conditions at the lead top and bottom the temperature distribution with the variable z can be concluded.

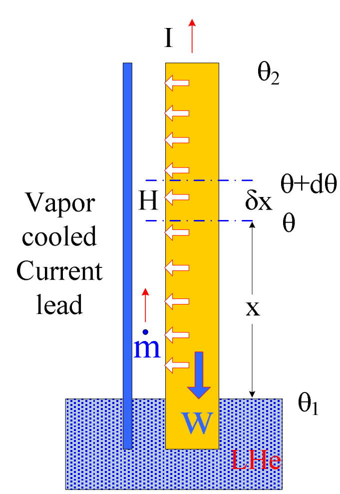

Figure 1: Schematic diagram of the one dimensional treatment on vapour cooled current lead and nomenclature used to derive the thermal balance equation.

MATERIAL AND OPTIMUM LEAD GEOMETRY

For the SuperKEKB IR SC correctors, three materials are investigated and their thermal conductivities are with great differences, as shown in Fig. 2. The brass is an alloy of copper and zinc with a content ratio of 90 to 10. Its electrical resistivity was measured at the LHe, liquid nitrogen (LN_2) and room temperature and the corresponding thermal conductivity was calculated according to Eq. 3, as marked by the blank rhombuses in Fig. 2. Some fitted points (triangles in Fig. 2) are added for the Ansys FEM simulation.

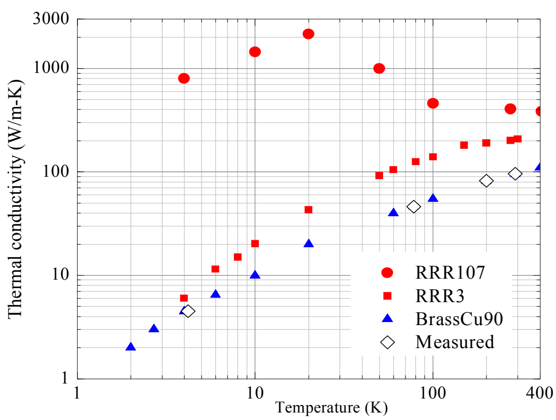

Figure 2: Thermal conductivity of three different materials: RRR~107 is the annealed pure copper of the common electrical grades; the RRR~3 is the phosphorus-deoxidized copper. The brass is the copper (with content of 90 %) and zinc alloy and adopted for our R&D.

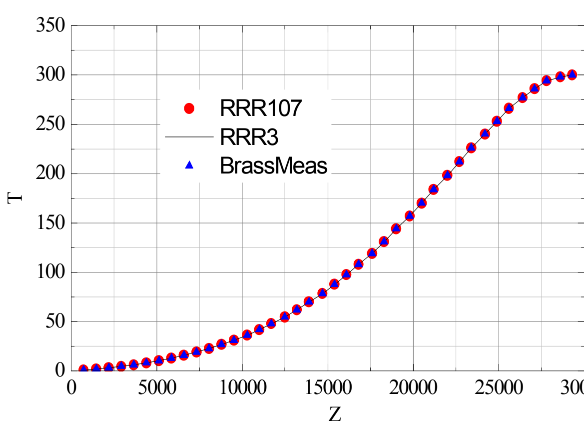

Figure 3: Temperature distribution with the parameter of z for leads to carrying optimum current. (For easily distinguishing, the scatter marks with distinct sizes and line are used.)

By minimizing the heat leak to the cold end with respect to Z_2 (at the lead top), a set of the parameters can be obtained and result in an optimum lead design. As the thermal property of material is included in the definition of z in Eq. 4, the temperature profile over z is independent with materials. The temperature distributions of the three materials to carry the optimum current with the parameter z are all the same as shown in Fig. 3 and at the lead top, the Z_2 value is 2.93×10^4. The heat leak of the optimum shape lead is about 1.04×10^{-3} W/A, which is constant for all materials obeying the Weidemann-Franz Law.

With the temperature profile over the parameter z, the optimum physical lead geometry can be obtained by integrating Eq. 4

$$\frac{Ix}{A} = \int k(\theta)dz \qquad (5)$$

As shown in Fig. 3, the variation of θ with z has been calculated according to the solution of the thermal equation and optimum conditions. The relations between $k(\theta)$ and z can be established by the intermediate variable of temperature and the $k(\theta)$ variations of three materials with the parameter z are plotted in Fig. 4. The integration of the right term of Eq. 5 for a kind of material is the area below the curve and the numerical calculation can be performed for estimation of the optimum shape factors, as listed in Table 1.

The correction coils of the Super-KEKB IR magnet system are designed with current of 50 A. According to the size of the KEKB cryostat, the lead length is selected as 690 mm. With the phosphorus deoxidized copper of the residual resistance ratio (RRR) of about 3 which is widely adopted for the vapor cooled leads, the lead optimum cross section area is only 9.86 mm^2. The small cross section is hard to bear the mechanical force especially at the connection ends and also limits the helium channel area for heat transfer. The further lower thermal conductivity should be copper alloy rather than copper. In this research, brass with 90 % copper content is chosen. With this brass material, the optimum cross section area is much larger and reaches 24.3 mm^2 as listed in Table 1.

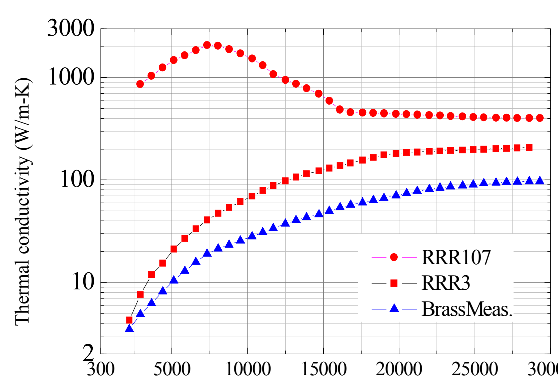

Figure 4: Variation of thermal conductivities of three materials with the parameter z.

Table 1: Optimum shape factors, cross section areas for 50 A and 690 mm and heat leaks at zero current of the three materials.

Material	Copper		Brass
	RRR~107	RRR~3	Cu~90 %
Optimum shape factor (A/m)	2.6×10^{7}	3.5×10^{6}	1.42×10^{6}
Cross section area of current (mm^2)	1.33	9.86	24.3
Heat leak at zero current (W/A)	0.667×10^{-3}	0.413×10^{-3}	0.403×10^{-3}

The IR correction coils are designed with the rated current of 50 A but they are not always operated at the full duty. It is important to know their heat leaks at zero current. The condition at zero current can be described by the Eq. 2 with the Joule heating term equal to zero. The solution with the optimum shape for the given current and numerical integration like that on Eq. 5 can be carried out. The heat leak at zero current depends on the material property, unlike the heat leak at the optimum current, as presented in Table 1 for the three materials. Compared with copper (RRR~3), the heat leak at zero current of the brass material is not increased although it has a twice larger cross section area.

Table 2: Design parameters of two structures (A and B).

Item	A	B
Operation current (A)	50	50
Optimum current (A)	51.78	50.13
Effective length (mm)	690	690
Helium cross section (mm^2)	10	9.6
Brass cross section (mm^2)	25.2	24.4
Ratio of helium to brass	0.397	0.393
Cooling helium flow (mg/g)	2.5	2.5
Heat exchanging area (m^2)	0.02	0.021

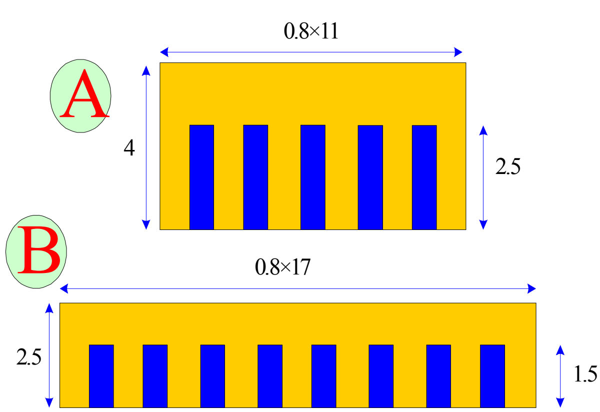

Figure 5: Two structures cross section of 50 A. The upper part of the figure is named Structure A and the lower part is B, as marked in the figure.

TWO STRUCTURES AND THERMAL AND FLOW CONDITIONS

With the optimum cross section area for 50 A, two structures are designed as illustrated in Fig. 5 and their main parameters are listed in Table 2. The areas of helium and brass are designed to almost the same and the operation currents of 50 A are very close to the optimum currents of the two structures of 51.78 A and 50.13 A, respectively. In the structures, the brass fins and the helium channels interlace with one another to ensure that the heat transfer area is enough.

The Reynolds number can be calculated according to the formula $Re=4m/\eta\text{-}P$ where m is the vapour mass flow rate, η is the viscosity and P is the perimeter. The Reynolds numbers of two structures with 2.5 mg/s flow at 5 K are calculated and listed in Table 3. The Reynolds numbers of helium flow decrease gradually up the lead as the ascending temperature raises its viscosity. As they are far less than the characteristic value of 2000, the vapour flow is laminar. The convective heat transfer coefficient is approximately independent of the flow velocity and is given by

$$h=\frac{4\lambda}{D} \qquad (6)$$

where λ is the thermal conductivity of helium gas and D is the hydraulic diameter. For a conservative estimate of h, the values at 5 K are calculated and are 38.2 and 39.8 W/m^2-K, respectively as listed in Table 3.

Table 3: Thermal and flow parameters with 2.5 mg/s helium vapour at 1.02 bar and 5 K.

Item	A	B
Reynolds number	220.2	197.5
Convective heat transfer coefficient (W/m^2-K)	38.2	39.8
Heat transfer efficiency	0.967	0.968

The heat transfer efficiency f can be derived from the definition and given by

$$f=\left(1+\frac{2w_0u}{PhX_2}\right)^{-1} \qquad (7)$$

where w_0 is the heat leak to the LHe, u is the helium ratio of specific heat to latent heat of evaporation, P is the cooled perimeter and X_2 is the top length.

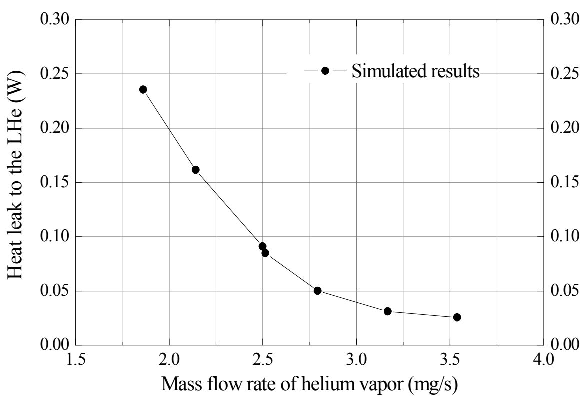

Figure 6: Heat leak to the cold end by the FEM simulation on the structure A.

As shown in Eq. 6, the convective heat transfer coefficient is independent of flow conditions and only related to the thermal conductivity of helium gas. The thermal conductivity of helium increases as the temperature goes up. So the minimum value of the efficiency is at the cold end. In Table 1, the heat transfer efficiencies of both structures are listed at 5 K and more than 0.96. Actually, when the helium temperature is higher than 30 K with its thermal conductivity of 0.034 W/m-K, the efficiency can just reach 0.99. At the lead cold end, the heat transfer efficiency is a little lower than the expected. The heat leak to the cold end will increase, which are demonstrated by the FEM simulation as shown in Fig. 6. At the optimum helium vapour flow of 2.5 mg/s, the heat leak is 0.08 W for 50 A and larger than the 1.04 W/kA. In the future plan, high temperature superconducting (HTS) wire is proposed to the lead cold end.

CONCLUSION

Based on the one dimensional model of the vapour cooled current lead, the general thermal equilibrium equation is reviewed and introduced. For the current lead design of the Super-KEKB IR correction coils, the three kinds of material are investigated and their optimum shape factors are resulted in. The brass with copper content of 90 % is chosen because of its corresponding large cross section area of 24.3 mm^2 for 50 A. Two structures are designed and the theoretical analysis is performed on their thermal and flow conditions, by which the laminar flow is confirmed. The formula of heat transfer efficiency is introduced and the minimum value exists at the cold end. At 5 K they are about 0.96 and at 30 K they just reach 0.99. As a result the heat leak to the cold end is increased. In the future research plan, HTS wire will be applied to the cold end of the lead.

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