OPTIMAL CURRENT-LEAD DESIGN FOR THE ROLLS OF PIERCED-METAL SHEET

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ABSTRACT

An optimal current-lead design based on a spiral roll-up of pierced-metal sheet is presented wherein full consideration is given to the geometric shape and to the convective heat transfer to vapor permeating the lead. This lead design called PJR (pierced "jelly-roll") is an attractive option to a variety of superconducting systems because of its low cost, ease of fabrication, mechanical ruggedness, and thermal stability. Energy balance equations for this lead are integrated with the temperature-dependent properties of the sheet metal. The effect of convective cooling with the extended surface area resulting from the metal piercing is included in terms of a new dimensionless parameter. The optimal heat flow distribution and the corresponding geometric lead parameter that minimizes the cooling load are calculated. Design data are presented for various geometric conditions and lead materials.

KEYWORDS: Current Leads, Heat Transfer, Vapor Cooling, Conduction, Extended Surface, Optimization, Pierced Metal
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INTRODUCTION

Current leads are the key components to deliver electrical power from room temperature to a superconducting magnet at cryogenic temperatures. Since the heat leak through the leads is a major source of cooling load for many high-field magnets, a great variety of lead designs to minimize the cryogenic load have been proposed and developed over decades [1-12]. A standard design of vapor-cooled metallic leads is based on the assumption that the convection

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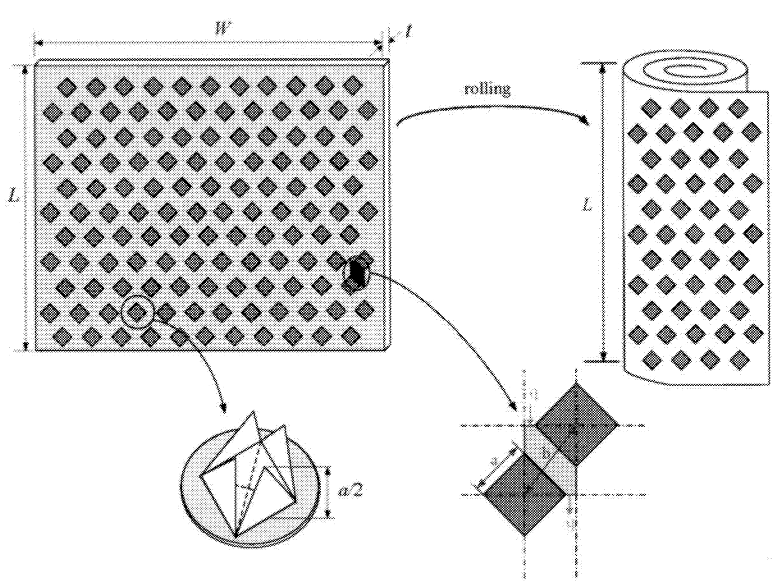


FIGURE 1. Schematic of pierced "jelly-roll" (PJR) current lead.

heat transfer of boil-off gas is perfect, or the vapor has the same temperature as the conductor surface at any axial location [1-4]. Even though this ideal assumption may be exactly realized in practice, numerous design efforts have been directed to improving heat transfer by fabricating the leads with great surface area (such as metal sheets, wires, and braids), adding extended surfaces (such as longitudinal or spiral fins), or controlling the fluid flow (such as tortuous or porous passages and flow agitators) [3-8].

One of the present authors has recently developed a new concept of lead design based on a spiral roll-up of pierced metal sheet (called pierced "jelly-roll" or PJR), as shown in FIGURE 1 [7,8]. A hexagonal array of square holes was produced on a copper sheet with special tooling and the pierced sheet is rolled on a central tube. No metal is actually removed in the piercing process so that the 4-pointed "crowns" play the role of spacers to provide a uniform cooling channel as well as extended surfaces to augment the convective cooling. For any given thickness of sheet, the piercing effectively reduces the (electrical and thermal) conduction cross-section, but the local heat capacity is enhanced because the full volume of metal is retained. Several pairs of prototype leads for up to 13 kA were successfully tested at CERN (LHC) and NHMFL (45T Hybrid Magnet). We evaluate that convective cooling of these PJR leads is excellent in comparison with other competing commercial leads [9].

The improvement of vapor cooling in current leads could reduce the thermal load at the cold-end. It is very crucial, however, that the reduction of the cryogenic load is effective only if the leads are optimally designed in accordance with the vapor-cooling condition. In other words, a simple enhancement of vapor cooling with the corresponding modification of the leads does not guarantee any savings in the heat load, or may end up with even poorer cryogenic design in a certain situation. Our latest analytical work has revealed that the optimal lead parameter could be notably different from the theoretical value for perfect heat transfer, even when the convective cooling is reasonably effective [9].

This study is proposed to quantitatively estimate the convection heat transfer in the cooling channel of the PJR lead design, which will lead to optimal design parameters for various geometric conditions and lead materials. The main focus will be on standard (helium or nitrogen) vapor-cooled leads, but conduction-cooled PJT leads will be considered as well for a special case where the thermal stability from an excessive fault current is significant. These results will contribute directly for an accurate and optimal design, and also broaden the application range of the PJR leads.

ANALYSIS

The steady-state energy balance equations for a vapor-cooled current lead can be written in terms of conductor temperature (T) and vapor temperature (T_g) as

$$\frac{d}{dx}\left(kA_e\frac{dT}{dx}\right)+\frac{\rho I^2}{A_e}-hP_e\left(T-T_g\right)=0 \tag{1}$$

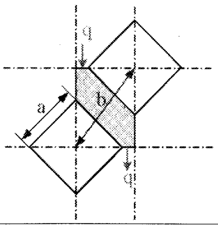
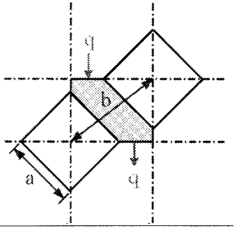
$$-\dot{m}C_P\frac{dT_g}{dx}+hP_e\left(T-T_g\right)=0 \tag{2}$$

where the thermal conductivity, k, and the electrical resistivity, ρ, of the sheet metal are temperature-dependent, and $\dot{m}C_p$ is the product of mass flow rate and specific heat of the cooling vapor. A_e denotes the effective cross-sectional area of electrical and thermal conduction in the axial direction, which can be calculated by finite element methods. TABLE 1 shows some values of the ratio of effective cross-section, f, by which A_e can be obtained as

$$A_e = f\cdot W\cdot t \tag{3}$$

where W and t are the width (perpendicular to the rolling axis) and thickness of metal sheet, respectively. The f value is a function of the ratio of the hole-to-hole distance, b, to a side of the square hole, a, and two planar directions are considered for the rolling of the hexagonal array. The rolling direction shown left in TABLE 1 is taken as this PJR design, because the f value is smaller due to more tortuous conduction-passage.

TABLE 1. Ratio of effective cross-section (f) in pierced-metal sheet for two planar directions and selected values of b/a.

Planar direction of rolling			
$\frac{b}{a}$	1.5	0.208	0.294
	2	0.586	0.647
	2.5	0.654	0.663

The effective perimeter of the pierced-metal sheet at a axial location, P_e, is defined as

$$P_e = P\left[1-\frac{P_f}{P}\left(1-\eta_f\right)\right] = 2W\left[1-\frac{2a^2}{3b^2}\left(1-\frac{2}{ma}\frac{I_1(ma)}{I_0(ma)}\right)\right] \tag{4}$$

where the total perimeter, *P*, is twice the width, P_f/P is identical to the area fraction of holes, and the fin efficiency, η_f, of a triangular fin is given in terms of modified Bessel functions of first kind and a parameter $m=\sqrt{2h/kt}$ [10].

The actual flow passage of cooling vapor in this lead is very complex and tortuous because of the crowns and holes, but its flow cross-section may be approximated as a rectangle whose height is *a*/2 and length is (*b*-*a*), as shown in FIGURE 1. The hydraulic diameter of the rectangular channel is given by

$$D_h \approx \frac{2a(b-a)}{2b-a}. \tag{5}$$

The convection heat transfer coefficient, *h*, is estimated in terms of D_h from the relations

$$h=\begin{cases} \dfrac{k_g}{D_h}Nu_L & \text{(laminar)} \\ 0.023\dfrac{k_g}{D_h}\left[\dfrac{4\dot{m}}{\mu N(2b-a)}\right]^{0.8}\mathrm{Pr}^{1/3} & \text{(turbulent)} \end{cases} \tag{6}$$

where Nu_L is a constant for a given aspect ratio of rectangle [10].

In order to obviate the implicit complexity due to the temperature-dependent properties and coefficients, the variables are now transformed from $T(x)$ and $T_g(x)$ to $q(T)$and $T_g(T)$, where $q(T)$ is heat flow per unit current towards the cold end,

$$q(T)=\frac{kA_e}{I}\frac{dT}{dx}. \tag{7}$$

Equations (1) and (2) becomes

$$\frac{dq}{dT}=L_0\left(Ch\frac{T-T_g}{q}-\frac{T}{q}\right) \tag{8}$$

$$\frac{dT_g}{dT}=Ch\cdot L_0\frac{h_{fg}}{C_P}\frac{T-T_g}{q\cdot q_L} \tag{9}$$

respectively, where *Ch* is a newly defined dimensionless number, called "Convection heat transfer (or Chang) number" in current-lead design [9],

$$Ch \equiv \frac{hP_e kA_e}{I^2 L_0} \tag{10}$$

and L_0 is the Lorenz number as a function of temperature

$$L_0(T)=\frac{k(T)\rho(T)}{T}. \tag{11}$$

The *Ch* number is an index to indicate the relative magnitude of the convective cooling to the Joule heating, because

$$Ch=\frac{hP_eT}{\rho I^2/A} \tag{12}$$

from equation (11). If *Ch* >>1, the convective cooling is dominant or a perfect heat transfer may well be justified. If *Ch* <<1, on the other hand, the convective cooling is negligible or the lead may well be considered conduction-cooled. The boundary conditions at the cold end are given by $\dot{m}\cdot h_{fg}=I\cdot q_L$, and $T_g(T_L)=T_L$, and the optimal condition to minimize the heat load at the cold end is $q(T_H)=0$.

The final steps of this analysis are to determine the optimal heat flow distribution by numerical integration of equations (8) and (9), and to calculate the corresponding optimum lead parameter. The lead parameter of PJR is defined here as the product of nominal current density (i.e. the current divided by cross-sectional area of the metal sheet before piercing) and axial length, as calculated by

$$\left(\frac{IL}{Wt}\right)_{opt}=\int_{T_L}^{T_H}\frac{k(T)}{q(T)}dT. \tag{13}$$

RESULTS AND DISCUSSION

Vapor-cooled PJR

FIGURE 2 demonstrates an example of the optimized results for nitrogen-cooled PJR leads. These leads are applicable not only to the HTS magnets in liquid nitrogen, but also to

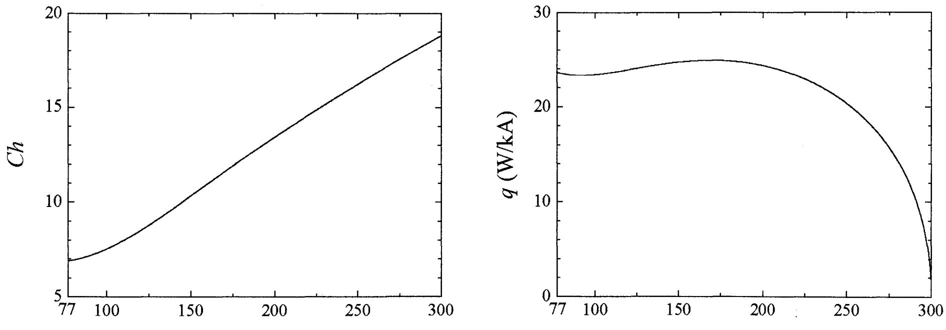


FIGURE 2. Optimized result for nitrogen-cooled PJR lead: (a) The *Ch* number (b) Optimal heat flow distribution.

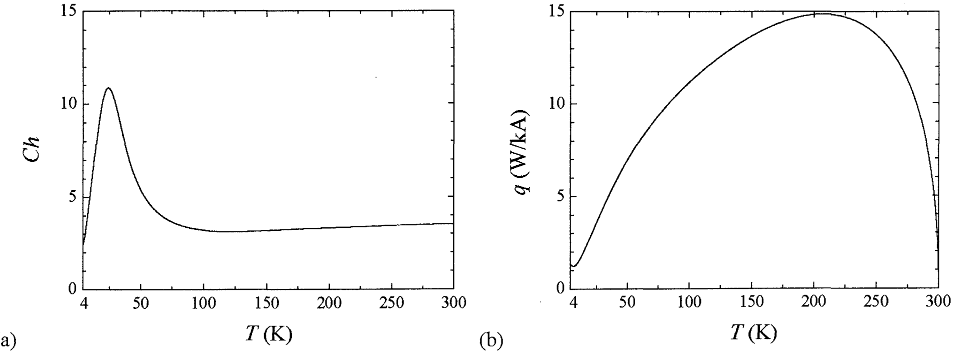


FIGURE 3. Optimized result for helium-cooled PJR lead: (a) The *Ch* number (b) Optimal heat flow distribution.

TABLE 2. Optimal lead parameter of vapor-cooled PJR lead for various *b*/*a* ratios and *RRR* values

		T_L = 77 K (N_2)				T_L = 4 K (He)			
b/*a*		1.5	2	2.5	perfect heat transfer	1.5	2	2.5	perfect heat transfer
RRR	20	27.1	27.0	26.9	25.2	136.6	137.1	137. 6	95.4
	40	28.2	28.2	28.1	26.4	158.6	157.9	157.7	132.4
	60	28.6	28.6	28.5	26.8	178.9	177.9	176.9	162.1
	80	28.7	28.8	28.7	27.1	198.4	196.7	196.1	188.3

the LTS magnets where the binary HTS leads are employed and the joint of HTS and metallic sections is cooled by liquid nitrogen [8,11]. FIGURES 3(a) and 3(b) are the plots of the *Ch* number and the optimal heat flow distribution as functions of temperature, respectively, for b/a = 2, t = 0.64 mm, and copper sheet with RRR = 60. The *Ch* number increases as the temperature increases and the average value of *Ch* is 12.6. The *Ch* values much greater than unity mean that the convective cooling is effective as discussed above. The corresponding heat flow of this optimized PJR is nearly constant for temperatures below 200 K and decreases to zero at room temperature. The heat flow at the cold end (or the minimum load under this optimal condition) is 23.6 W/kA, which is close to an ideal case of perfect heat transfer. [9]

The same set of results for helium-cooled PJR leads is shown in FIGURE 3. The *Ch* number has a local peak around 24 K, mainly due to the thermal conductivity of copper. Average *Ch* of this helium-cooled PJR is approximately 4.1, which is smaller than the average *Ch* of the nitrogen-cooled PJR, thus the overall convective cooling must be less effective. On the other hand, the *Ch* number is still greater than unity, which means that the convection to cooling vapor is dominant over the axial conduction in the lead. As a result, the cooling load at the cold end is not much different from the ideal minimum at 1.1 W/kA. [9]

A key point of this analysis that the optimal lead parameter is considerable different from the ideal (i.e. perfect heat transfer) case, even when the convective cooling may be very effective in current leads or *Ch*>>1. Exact optimal values of the lead parameter are calculated and listed in TABLE 2 for various geometric and material conditions in comparison with the perfect heat transfer cases. The reason for the difference (especially, for the helium-cooled

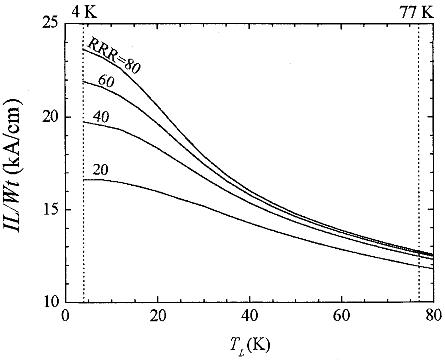


FIGURE 4. Optimal lead parameter of conduction-cooled PJR lead as a function of cold-end temperature.

PJR leads) is that the lead parameter is not a monotonically increasing function of the *Ch* number, but has a peak value at around *Ch* = 2 ~ 2.5. A more detailed explanation of these phenomena is available in our recent publication [9].

Conduction-cooled PJR

The PJR has many advantages over other vapor-cooled leads, but could also be used as conduction-cooled (or cryocooler-cooled) leads for special applications where thermal stability from disturbance and mechanical ruggedness are imperative. A superconducting fault current limiter (SFCL) is a such example, as the leads should be thermally and mechanically tolerable against an impulsive fault current. For the leads passing through vacuum, the optimal condition of conduction-cooled leads is determined simply by setting $Ch = 0$ in equation (8) and substituting the optimal $q(T)$ into equation (13) [12]. For the leads passing through a closed vapor-filled space where $Ch \ll 1$, the minor effect of natural convection of vapor can be incorporated by a perturbation method, as demonstrated by our previous publication [13].

Figure 4 plots the optimal lead parameter as a function of cold-end temperature for various RRR values of copper sheet, when $b/a = 2$. The lead parameter should be 12~13 kA/cm for liquid-nitrogen temperatures, and 17~23 kA/cm for liquid-helium temperatures, depending upon the RRR values between 20 and 80. Since the effective conduction area is smaller by the factor listed in TABLE 1, these values of lead parameter are smaller by the same factor than the standard conduction-cooled leads.

CONCLUSIONS

A comprehensive thermal design is performed on the PJR current leads. The geometric effect of the tortuous passage in thermal and electrical conduction is included with a finite element analysis, and the convection heat transfer coefficient is approximately calculated for the permeating vapor flow with existing correlations. Based upon this heat transfer information, we develop rigorously and quantitatively the unique optimal lead parameter for various geometric conditions and material properties. Since the convective cooling in the PJR leads is relatively effective, the heat load at the cold end is very close to the theoretical minimum obtained when a perfect heat transfer is assumed between the conductor and cooling vapor. On the other hand, the suggested values of PJR lead parameter to minimize the heat load could be considerably greater than the case of perfect heat transfer, depending upon the piercing options and the material properties.

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