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Effect of convection heat transfer on the design of vapor-cooled current leads

Ho-Myung Chang [a,*], Jung Joo Byun [a], Hong-Beom Jin [b]

[a] *Hong Ik University, Department of Mechanical Engineering, 72-1 Sangsu-Dong, Mapo-Ku, Seoul 121-791, Republic of Korea*
[b] *Duksung Co. Ltd., Kyungki-Do 430-040, Republic of Korea*

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Abstract

A general optimization method for vapor-cooled current leads is presented with taking into account the effect of convection heat transfer and extended surfaces. This analytical work is considered as a unified design method, since one formulation calculates the minimum heat load and the corresponding optimal design condition for arbitrary heat transfer condition, spanning two limiting cases—the zero convection (or conduction-cooled leads) and the perfect heat transfer. It is clearly shown that the augmentation of the convective cooling can reduce the heat load to a certain extent, but the optimum lead parameter required to minimize the heat load for the finite heat transfer may not exist between the two limiting values. A new dimensionless parameter called the *Ch* number is introduced to conveniently incorporate the convection effect into the optimization. The present method is demonstrated for two specific lead designs that have been recently developed for 10 kA level of applications.

Keywords: Convection (C); Heat transfer (C); Current leads (E)

1. Introduction

Current leads are the key components that supply electrical power from room temperature to a superconducting magnet at cryogenic temperature. 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 developed over the decades. The basic principles of optimization were reported earlier, especially for two limiting cases; vapor-cooled leads [1–4] and conduction-cooled (or uncooled) leads [2–4].

A standard design of vapor-cooled metallic leads is based on the assumption that the convection heat transfer of the boil-off gas is perfect or the vapor has the same temperature as the lead surface at any axial location [3]. Even though the ideal assumption may not be absolutely realized in practice, numerous design efforts have directed to the perfect heat transfer by fabricating the leads with greater surface area (such as metal sheets, wires, and braids [4]), adding the extended surfaces (such as longitudinal or spiral-fins [5,6] and pierced sheets [7,8]), or controlling the fluid flow (such as tortuous or porous passages and flow agitators [4]). It is generally known that the improvement of the lead-vapor heat transfer could reduce the heat load at the cold-end of the leads [1,2]. It is very crucial, however, to note 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 the vapor cooling without the corresponding modification of the leads does not guarantee any save in the heat load, or may end up with even poorer cryogenic design in some situation.

In spite of its significance, the effect of convection heat transfer on the optimization has not been so widely studied

* Corresponding author. Tel.: +82 2 320 1675; fax: +82 2 322 7003.
E-mail address: hmchang@hongik.ac.kr (H.-M. Chang).

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Nomenclature

A	cross-sectional area of lead [m^2]
a	short diagonal of hexagonal hole in pierced-metal sheet [m]
b	distance between hexagonal holes in pierced-metal sheet [m]
C_p	specific heat of vapor [J/kg K]
Ch	convection heat transfer (Chang) number, defined as $Ch \equiv \bar{h}P_e kA/I^2 L_c$
d	hydraulic diameter of cooling channel [m]
f	fraction of effective cross-sectional area in pierced-metal sheet
$\bar{h}$	average heat transfer coefficient [W/m^2 K]
h_{fg}	latent heat of vaporization [J/kg]
I	operating current [A]
I_0, I_1	modified Bessel functions of first kind
K_0, K_1	modified Bessel functions of second kind
k	thermal conductivity of lead material [W/m K]
k_g	thermal conductivity of cooling vapor [W/m K]
L	axial length of lead [m]
L_0	Lorenz number as a function of temperature [W Ω/K^2]
L_c	Lorenz constant [$=2.45\times10^{-8}$ W Ω/K^2]
m	fin parameter, defined as $m \equiv \sqrt{2\bar{h}/kt}$ [m^{-1}]
N	number of cooling channels for roll of pierced-metal sheet
Nu_d	Nusselt number based on d
$\dot{m}$	mass flow rate of vapor [kg/s]
P	total perimeter of vapor cooling [m]
P_e	effective perimeter of vapor cooling [m]
P_f	fin perimeter of vapor cooling [m]
p	pitch of spiral-fin [m]
Pr	Prandtl number
q	heat flow per unit current [W/A]
r_i, r_o	inner and our radius of spiral-fin [m]
T	temperature of lead [K]
T_g	temperature of vapor [K]
t	thickness of fin [m]
W	width (perpendicular to the lead length) of pierced-metal sheet [m]

Greek letters

μ	viscosity of vapor [Pa s]
ρ	electrical resistivity of lead material [Ω m]
η_f	fin efficiency

Subscripts

H	warm end of lead
L	cold-end of lead
min	minimum value
opt	optimum value

because of its analytical difficulties. An earlier theory is quoted in Wilson's book [1], where the effect of finite heat transfer was treated approximately with heat transfer efficiency. Buyanov [4] suggested a few simplified forms of analytical expression for the temperature difference between the lead and the cooling gas. Maehata et al. [5,6] presented a design chart for spiral-finned lead made of copper with different RRR values, derived from an engineering correlation for turbulent flow through a tube. Chang and Van Sciver [10] introduced an optimization theory for leads weakly cooled by natural convection in a closed vapor-filled space. A more systematic formulation was summarized in a recent publication [2], yet no quantitative information with a practical accuracy is available in the literature to our best knowledge.

This study has been proposed for a general design method for arbitrary cooling condition of metallic leads. In particular, we have tried first to examine the fundamental features of the convection heat transfer between the lead and vapor, and then to develop a single optimization theory that is applicable to any shapes of leads, any types of extended surfaces, any flow conditions, and any temperature-dependent properties of the lead materials. These results should be useful for the design of not only the metallic leads, but also the warmer metallic section of binary or hybrid HTS leads [2,8–11].

2. General analysis

2.1. Formulation

The steady energy balance equations are

$$\frac{\mathrm{d}}{\mathrm{d}x}\left(kA\frac{\mathrm{d}T}{\mathrm{d}x}\right) + \frac{\rho I^2}{A} - \bar{h}P_e(T - T_g) = 0 \tag{1}$$

for the lead, and

$$-\dot{m}C_p\frac{\mathrm{d}T_g}{\mathrm{d}x} + \bar{h}P_e(T - T_g) = 0 \tag{2}$$

for cooling vapor, as schematically shown in Fig. 1. In Eqs. (1) and (2), k and ρ are the (temperature-dependent) thermal conductivity and electrical resistivity of the lead material, respectively, and C_p is the specific heat of the cooling vapor. $\bar{h}P_e$ denotes the product of the (spatially) average heat transfer coefficient and the effective perimeter defined by

$$P_e = P\left[1 - \frac{P_f}{P}(1 - \eta_f)\right] \tag{3}$$

where P is the total perimeter and P_f is the perimeter of the extended surface. The fin efficiency, η_f, is defined as the ratio of the actual heat transfer to the maximum heat