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DESIGN PARAMETERS FOR GAS-COOLED ELECTRICAL LEADS OF THE g-2 MAGNETS

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This report presents the design parameters for a pair of 5300 A gas-cooled electrical leads for the g-2 solenoids and a pair of 2850 A leads for the inflector magnet. The lead design parameters are derived from a scale analysis of two one-dimensional, thermo-fluid-electro-quasi-coupled, and non-linear differential equations. The analysis may apply to general gas-cooled electrical lead design. As an illustration, these design parameters are applied to multi-tube gas-cooled leads that are proposed for the g-2 solenoid magnet system. Multiple electrical current carrying tubes and multiple gas flow cooling channels will increase the lead current capacity and lead efficiency for enhanced heat transfer and low flow pressure drop.

INTRODUCTION

The g-2 storage ring magnet system consists of four large superconducting solenoids that are up to 15.1 m in diameter [1]. The four solenoids will be hooked in series and they will be powered through a single pair of 5300 A gas-cooled electrical leads. In addition there is an inflector magnet that is separately powered through a pair of 2850 A gas-cooled leads. Both sets of leads will be cooled using cold helium drawn directly from the forced two-phase helium cooling system used to cool the four solenoids and the inflector.

Tubular gas-cooled electrical leads have been used at various laboratories since the mid 1960's to power superconducting magnets. An insert was used to improve the heat transfer in tube leads in the late 1960's to increase the lead current by a factor of as much as three. The use of annular flow leads was described in the literature by Smits et al. in 1981 [2]. The concept of bundling tube leads to increase their current was applied to curved gas-cooled leads for the PEP-4 solenoid [2].

Gas-cooled electrical leads of many different kinds for superconducting magnets have been studied for over 25 years. M. N. Wilson's book [3] is an excellent source of information concerning the design of boil-off-gas-cooled electrical leads. Some lead design parameters for the "ideal gas-cooled leads" (i.e. the heat transfer coefficient is infinite) was given in the book. D. P. Sekulic et al. discussed the optimal thermal design of the "non-ideal gas-cooled leads" (i.e. the heat transfer coefficient is finite) using the entropy analysis [4].

This report presents some design parameters for non-ideal gas-cooled leads derived from a scale analysis on the energy balance, which may be applied to the general gas-cooled electrical lead design and allow one to get some design parameters in fair accuracy even before doing any detailed numerical computations. This analysis is based on the following assumptions: 1) Overall electrical heat generation in the lead is approximately equal to the overall convective heat flux from the lead to the cooling gas; 2) Overall convective heat flux of the lead is approximately equal to the overall enthalpy

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increase of the cooling gas; 3) Overall electrical heat generation of the lead is approximately twice as much as the overall conductive heat dissipation through the lead between the high and low temperature levels.

GAS-COOLED LEAD MODEL

The mathematical model in non-dimensional variables for gas-cooled electrical lead may be described by a set of two thermo-fluid-electro-quasi-coupled, non-linear, one-dimensional differential equations that are derived from an energy balance applied to a differential element of the electrical lead and the cooling gas flow. It takes the following form:

$$\frac{d}{d\xi} \left[a(\Theta) \frac{d\Theta}{d\xi} \right] + b(\Theta) \Gamma^* = Bi^* (\Theta - \theta) \quad (1)$$

$$\frac{d\theta}{d\xi} = St^* (\Theta - \theta) \quad (2)$$

where Θ is the non-dimensional lead temperature, $\Theta = (T_s - T_c)/(T_H - T_c)$. T_H and T_c are the temperatures of lead at top and bottom, respectively. T_s is the variable temperature of metal lead. θ is the non-dimensional cooling gas temperature, $\theta = (T_g - T_c)/(T_H - T_c)$. T_g is the variable temperature of gas flow. ξ is the non-dimensional axial coordinate, $\xi = x/L$. $a(\Theta)$ is the non-dimensional thermal conductivity of the lead, $a(\Theta) = k(\Theta)/k_{ref}$. $b(\Theta)$ is the non-dimensional electrical resistivity of lead, $b(\Theta) = \rho(\Theta)/\rho_{ref}$. $k(\Theta)$ and $\rho(\Theta)$ are variable values for lead metal thermal conductivity and electrical resistivity, respectively. k_{ref} and ρ_{ref} are their reference values taken at the same reference temperature T_{ref} . Γ^* , Bi^* and St^* are non-dimensional functions which are given in the next few paragraphs.

LEAD DESIGN PARAMETERS

Electrical Heat Dissipation Parameter - IL/A_s

The first non-dimensional function Γ^* defined by Eq. (1) and known as the electrical power dissipation function relates the Joule heating to heat conducted down the lead. Γ^* takes the following form:

$$\Gamma^* = \frac{(IL/A_s)^2 \rho_{ref}}{k_{ref}(T_H - T_c)} = \frac{(L/A_s) I^2 \rho_{ref}}{A_s k_{ref}(T_H - T_c)/L} = \frac{\text{Electrical heat generation}}{\text{Conductive heat dissipation}} = S_2 \quad (3)$$

where I is the electrical current. L is the length of the lead. A_s is the lead cross-section area. The IL/A_s term appeared in the function is found extensively in the gas-cooled lead literature. As pointed out earlier the electrical heat generation is approximately twice as much as the conductive heat dissipation, i.e. $S_2 = 2$ and thus $\Gamma^* = 2$, approximately. IL/A_s thus takes the following form:

$$IL/A_s = [S_2 k_{ref}(T_H - T_c) / \rho_{ref}]^{0.5} = k_{ref} [S_2 (T_H - T_c) / L \rho_{ref}]^{0.5} = [S_2 L \rho_{ref} (T_H - T_c)]^{0.5} / \rho_{ref} \quad (4)$$

The Wiedemann-Franz law, $k\rho = LoT$ ($Lo = 2.45 \times 10^{-8} \text{ W } \Omega \text{ K}^{-2}$), has been applied to the last two terms of Eq. (4). The parameter IL/A_s for a lead can vary depending on the metal in the leads. The point is that for a given electrical current, there is a given value for L/A_s . The value for IL/A_s for phosphorous deoxidized copper given in Wilson's book is $3.5 \times 10^6 \text{ A m}^{-1}$.

Heat Exchange Parameter - PL^2/A_s

The second non-dimensional function is the modified Biot number Bi^* or heat exchange function which is defined in Eq. 1 as follows:

$$Bi^* = \frac{hPL^2}{k_{ref}A_g} = \frac{hPL(T_g - T_g)[(T_H - T_C)/(T_g - T_g)]}{A_g k_{ref}(T_H - T_C)/L} = \frac{\text{Convective heat flux}}{\text{Conductive heat dissipation}} \cdot R_T = S_2 \cdot R_T \quad (5)$$

where h is the heat transfer coefficient. P is the wetted perimeter. R_T is the temperature ratio which is defined as $R_T = (T_H - T_C)/(T_g - T_g)$. For a typical gas cooled lead $T_H - T_C = 300$ K and $T_g - T_g = 3$ to 6 K for a well designed lead. A reasonable design value for R_T is about 100. If one lets $S_2 = 2$ and $Bi^* = 200$, approximately, the following relationship holds: $PL^2/A_g = 200 k_{ref}/h$.

Gas Cooling Parameter - PL/M_g

The third non-dimensional function is the modified Stanton number St^* or gas cooling function which is defined in Eq. (2) as following:

$$St^* = \frac{hPL}{M_g C_p} = \frac{hPL(T_g - T_g)[(T_H - T_C)/(T_g - T_g)]}{M_g C_p (T_H - T_C)} = \frac{\text{Convective heat flux}}{\text{Gas enthalpy increase}} \cdot R_T = S_1 \cdot R_T \quad (6)$$

where M_g is the gas mass flow rate. C_p is the specific heat of cooling gas. Since R_T has value of about 100, if one lets $S_1 = 1$, the modified Stanton number St^* has a value of about 100. Thus, the following relationship holds: $PL/M_g = 100 C_p/h$.

Mass Flow Rate Parameter - M_g/I

The mass flow rate parameter is defined by the ratio of the modified Biot number, Bi^* , and the modified Stanton number, St^* :

$$\frac{Bi^*}{St^*} = \frac{M_g C_p L}{A_g k_{ref}} = \frac{M_g C_p (T_H - T_C)}{A_g k_{ref} (T_H - T_C)/L} = \frac{\text{Gas enthalpy increase}}{\text{Conductive heat dissipation}} = S_2 = \frac{IL}{A_g} \frac{M_g}{I} \frac{C_p}{k_{ref}} \quad (7)$$

If one lets $S_2 = 2$, and $Bi^*/St^* = 2$, the following expression can be derived: $M_g/I = 2(k_{ref}/C_p)/(IL/A_g) = (S_2 Lo T_{ref}/\Delta T)^{0.5}/C_p$. The mass flow rate per unit current can be estimated by using Eq. (7).

Lead Efficiency Parameter - $(IL/A_g)(L/M_g)$

The ratio of the electrical heat generation parameter and the mass flow rate parameter takes following form:

$$\Gamma \cdot \frac{St^*}{Bi^*} = \frac{(L/A_g) I^2 \rho_{ref}}{M_g C_p (T_H - T_C)} = \frac{\text{Electrical heat generation}}{\text{Gas enthalpy increase}} = S_1 \quad (8)$$

If one lets $S_1 = 1$, and $\Gamma \cdot St^*/Bi^* = 1$, the following expression can be derived: $(IL/A_g)(L/M_g) = C_p(T_H - T_C)/\rho_{ref} = C_p(T_H - T_C) k_{ref}/(Lo T_{ref})$.

MULTI-TUBE GAS-COOLED LEADS

As an illustration, these design parameters are applied to the multi-tube gas-cooled leads that are proposed for the g-2 solenoid magnet system. A combination of three tubes with an insert tube which does not carry the electrical current has been chosen. Table 1 compares the performance of the gas-cooled leads in different combinations which may be used for the selection of multi-tube forms. Table 2 gives the geometries of a three-tube lead using standard Type M copper tube ($RRR = 6.365$). The

number of tube bundles was set at five for each 5300 A g-2 solenoid gas cooled lead. A design current of 1060 A per tube in the bundle was used to determine the design of the nested tube set. For each 2850 A g-2 inflector lead, the number of tube bundles can be set at three. Table 3 gives the physical parameters of the g-2 leads [5]. Table 4 shows the numerical values of the modified heat transfer functions of the g-2 lead. Table 5 shows the numerical values of the design parameters of the g-2 leads using Eqs. (3) to (8).

Table 1 Comparison of the performance of the gas-cooled leads in different combinations

Tube Form	P/A_s	A_s/I
One annular gas flow channel/one electrical current flow tube	1	1
Two annular gas flow channels/two electrical current flow tubes	3/2	2
Two annular gas flow channels/three electrical current flow tubes	4/3	3
Three annular gas flow channels/three electrical current flow tubes	5/3	3

Table 2 Geometries of standard Type M copper tubes used for the g-2 gas-cooled electrical leads

	Outer Tube	Mid Tube	Inner Tube	Insert
Tube O.D. (mm)	22.225	19.050	15.875	12.700
Tube I.D. (mm)	20.599	17.526	14.453	10.210

Table 3 Physical parameters of the g-2 gas-cooled electrical leads

L (m)	P (m)	A_s (m ²)	A_g (m ²)	M_g (g/s)	h (W/m ² -K)	I (A)	T_{ref} (K)	ρ_{ref} (Ω m)	k_{ref} (W/m-K)
0.437	0.275	1.32×10^{-4}	1.29×10^{-4}	0.050	198	1060	273	1.81×10^{-8}	369.8

Table 4 Numerical values of the modified heat transfer functions of the g-2 gas-cooled electrical leads

Γ^*	Bi^*	St^*	Bi^*/St^*	Γ^*St^*/Bi^*
2.03	212	92	2.3	0.88

Table 5 Numerical values of the design parameters of the g-2 gas-cooled electrical leads

IL/A_s (A/m)	PL^2/A_s (m)	PL/M_g (m ² -sec/kg)	M_g/I (kg/sec-A)	$(IL/A_s)/(I/M_g)$
3.5×10^6	396	2403	4.72×10^{-8}	7.42×10^{13}
$(S_2 k_{ref} \Delta T / \rho_{ref})^{0.5}$	$(S_2 k_{ref} / h) \times 100$	$(Cp/h) \times 100$	$(S_2 L o T_{ref} / \Delta T)^{0.5} / Cp$	$Cp \Delta T / \rho_{ref}$
3.48×10^6	374	2626	4.09×10^{-8}	8.49×10^{13}

CONCLUSION

Gas-cooled electrical leads for the g-2 solenoids and the inflector can be built using bundled tube leads where each of the tubes in the bundle consists of nested standard Type M copper tubes. Both of the 5300 A solenoid leads will fit in a cylinder that is 120 mm in diameter by 750 mm long. Both the 2850 A inflector leads will fit within a cylinder that is 100 mm in diameter by 650 mm long. Superconductor will be attached to the tubes in order to reduce the heat leak into the cryostat and to reduce the helium needed to cool the leads.

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