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THE ROLE OF SUPERCONDUCTOR IN REDUCING THE REFRIGERATION NEEDED TO COOL THE LEADS OF A SUPERCONDUCTING MAGNET

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The electrical lead represents a major heat load and a major user of refrigeration in a superconducting magnet system. It has been postulated that high $T_c$ superconductor could be used to reduce the refrigeration required by the leads in a conventional superconducting magnet. Substantial refrigeration reductions appear possible using superconductor in conjunction with gas cooled leads provided the gas is drawn from the refrigerator at a temperature just below $T_c$. Even with conventional superconductors, refrigeration reductions of a factor of two appear to be possible using this technique.

BACKGROUND

Helium gas cooled leads have long been used to power bath cooled superconducting magnets. The helium gas from boiling is sent up the lead and is used to intercept joule heating and heat conducted down the leads. As a result, the helium boil off in the cryostat can be reduced substantially (up to a factor of 50 over a cryostat with non-gas cooled leads). Superconductor, added to a conventional gas cooled lead, will reduce the helium boil off through the lead, but this gain is relatively small. Cooling the upper end of a gas cooled lead with liquid nitrogen only reduces the helium cooling requirement by 15 percent.

If high $T_c$ superconductors, which have a zero resistance state at temperatures up to 125 K, can be used to carry the current, the need for lead cooling can be reduced even more. $^1$ $^2$ $^3$ This report shows circumstances under which large reductions in the refrigeration can be made using even conventional superconductor in conjunction with helium gas cooled electrical leads.

INPUT POWER FOR REFRIGERATION AND LIQUEFACTION

The refrigeration input power is the only reasonable criteria to be used to assess the performance of the superconductor on gas cooled leads. The input power to a given refrigerator is a function of a number of criteria, the most important of which is the amount of refrigeration being produced by the refrigeration plant. The refrigeration input power RIP can be stated as follows:

$$ RIP = \frac{CIP}{\eta} \quad (1) $$

where $CIP$ is the carnot input power and $\eta$ is the refrigerator efficiency. According to Strobridge$^4$, $\eta$ is a function of $CIP$. (When $CIP$ is 1 kW, $\eta$ will vary from 0.05 to 0.08. When $CIP$ is 100 kW, $\eta$ will vary from 0.12 to 0.18.)

The carnot input power $CIP$ can be stated as follows:

$$ CIP = \dot{m} CIE \quad (2) $$

where $\dot{m}$ is the fluid mass flow from the refrigerator to the load, and $CIE$ is the carnot input energy per unit mass of the fluid. The carnot input energy for a given liquefied fluid:
\[ CIE = CIE_1 + C_p TH \ln \left( \frac{TH}{T_b} \right) - C_p (TH - Tb) \]  

where \( CIE_1 \) is the carnot input energy needed to liquefy a unit mass of cold gas at the liquid boiling temperature:

\[ CIE_1 = \frac{\Delta h_{fg}(TH - Tb)}{T_b} \]  

where \( TH \) is the heat rejection temperature, \( T_b \) is the fluid boiling temperature, \( C_p \) is the specific heat at constant pressure, and \( \Delta h_{fg} \) is the heat of vaporization of the fluid at \( T_b \).

If boiling liquid is used to cool an object and the gas is vented at the boiling temperature \( T_b \), the energy removed per unit fluid mass \( AR_1 \) is:

\[ AR_1 = \Delta h_{fg} \]  

The maximum available refrigeration from a fluid \( AR \) is when both the sensible heat and the heat of vaporization are both used to cool the object when the fluid enters the system as a liquid at a temperature \( T_b \) and exists as a gas at temperature \( T_H \):

\[ AR = AR_1 + C_p (TH - Tb) \]  

WORKING FLUIDS FOR SUPERCONDUCTING MAGNETS

Table 1 shows the properties of four low boiling temperature gases: helium, para-hydrogen, neon and nitrogen. Helium is the working fluid of choice for cooling conventional superconducting devices. Hydrogen, neon and nitrogen can be considered for cooling high \( T_c \) superconducting devices (when they exist).

<table>
<thead>
<tr>
<th>Properties of Helium, Hydrogen, Neon and Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling Temperature at 1 atm (K)</td>
</tr>
<tr>
<td>Molecular Weight</td>
</tr>
<tr>
<td>Ratio of Specific Heats</td>
</tr>
<tr>
<td>Heat of Vaporization (Jg(^{-1}))</td>
</tr>
<tr>
<td>Specific Heat at Constant Pressure (Jg(^{-1})K(^{-1}))</td>
</tr>
</tbody>
</table>

Table 2 compares the carnot input energy for liquefaction (when the boil off gas is returned to the liquefier warm) and refrigeration (when the boil off gas is returned to the liquefier at the boiling temperature of the fluid). Refrigeration uses less input energy per unit mass than does liquefaction. Table 2 also compares maximum available refrigeration from a gram of liquid which is boiled and heated to 300 K. The refrigeration per unit mass for liquid vaporization is also shown in Table 2.

<table>
<thead>
<tr>
<th>Carnot Input energy for liquefaction, carnot Input energy for refrigeration and maximum available refrigeration for helium, hydrogen, neon and nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carnot Input Energy</td>
</tr>
<tr>
<td>For Liquefaction (Jg(^{-1}))</td>
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<tr>
<td>For Refrigeration (Jg(^{-1}))</td>
</tr>
<tr>
<td>Maximum Available</td>
</tr>
<tr>
<td>Refrigeration (Jg(^{-1}))</td>
</tr>
<tr>
<td>Refrigeration from Liquid Vaporization (Jg(^{-1}))</td>
</tr>
</tbody>
</table>
Conventional gas cooled leads have cold gas fed into the lead only at the bottom and only at the lowest temperature (the boiling temperature of the gas). The operation of conventional leads on a refrigerator is illustrated in Figure 1. The carnot input power is proportional to the gas flow needed to keep the leads cool (6562 Jg\(^{-1}\) for helium).

An alternative approach is to use helium from the refrigerator at a higher temperature to cool the conventional copper lead. Conventional or high \(T_c\) superconductor can be used to bridge the gap between the temperature of the gas which is being supplied by the refrigerator and the helium bath. A small flow of helium from the bath may be needed to intercept the heat leaking down the superconductor and its supporting metal tube. Figure 2 illustrates this concept of lead cooling. The support tube can be made from a low thermal conductivity metal such as brass, or stainless steel.

The heat leak into the helium bath and the amount of helium needed to cool the lead from 4.2 K to the input temperature of the gas from the refrigerator (this temperature is below the superconductor critical temperature so that the lead between the helium bath and the gas input from the refrigerator will always be superconducting) is dependent on the thermal conductivity of the material used to bridge the section.

The heat leak down a section of lead with electrical resistivity \(\rho\) independent of temperature can be stated as follows:

\[
Q = \frac{L}{2\rho} \left[ T_2^2 - T_b^2 \right] \frac{A_c}{L}
\]

where \(Q\) is the heat flow down a piece of lead of length \(L\) and cross-sectional area \(A_c\). \(L\) is the Lorenz number (\(L = 2.45 \times 10^{-8}\) W ohm K\(^{-2}\)).

The cross-sectional area of the lower lead \(A_c\), is controlled by the need to protect the lower lead in the event that the superconductor on the lower lead turns normal.

The carnot input power can be calculated for leads which have gas entering at a temperature \(T_2\) from the refrigerator. (The lead between temperatures \(T_b\) and \(T_2\) is superconducting). The input power is:

\[
\text{carnot input power} = [C_p T_H \ln \left( \frac{T_H}{T_2} \right) - C_p (T_H - T_2) \ \text{r} \_2] + \frac{\text{CTE1} \ Q}{\Delta h_{fg}}
\]

where CTE is defined by Equation 3 and \(\text{r} \_2\) is defined by the operation of the upper lead.

The value of the carnot input power given by Equation 6 can be reduced further by cooling the lower lead as shown in Figure 2. This improvement can only be achieved when \(T_2\) is above 17 K.

Table 3 shows that large reductions of carnot input can be achieved by cooling the non-superconducting portion of the lead by gas drawn from a helium refrigerator at a temperature \(T_2\). Table 3 shows that even the use of conventional superconductors (\(T_c\) up to 23 K) can result in a reduction of the input power to a refrigerator by a factor of two. The use of high \(T_c\) superconducting materials can potentially result in a larger reduction in the refrigeration input power needed to cool the gas cooled leads.

The reduction of lead cooling refrigeration input power shown in Table 3 is not without cost. First, the highest temperature of the superconductor bridging the gap between \(T_2\) and \(T_b\) is higher than \(T_2\) because there has to be a temperature difference between the bottom of the upper lead and the gas stream entering at temperature \(T_2\) (about 3 degrees K). This temperature difference must be considered in the design. Second, the lead circuit shown in Figure 2 is unstable when the superconductor between temperature \(T_2\) and \(T_b\) becomes normal. If the high resistivity lead length and cross section are properly chosen, one can deal with the instability by increasing the
Fig. 1 Refrigerated Gas Cooled Leads with the Cooling Gas Drawn from Liquid Helium Boil Off

Fig. 2 Refrigerated Gas Cooled Leads with the Primary Cooling Gas Drawn from an Intermediate Temperature Point within the Refrigerator. Secondary Gas is Drawn from Liquid Helium Boil Off.
flow of gas $r_{h1}$ from the bath at a temperature $T_b$. This gas flow from the helium bath can be controlled by measuring the voltage drop along the lower lead.

**SUMMARY**

Superconductor mounted on conventional gas cooled leads does not improve the performance of these leads very much. If the resistive portion of a gas cooled lead is cooled by helium from the refrigerator entering at an intermediate temperature, a considerable reduction of the input power (to the refrigerator) needed to cool the leads can be achieved. Even conventional A-15 superconductors, properly used, can result in a reduction of input power by a factor of two.

**ACKNOWLEDGEMENTS**

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