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Superconducting Current Leads***

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Energy Technology Division

Argonne National Laboratory, Argonne, IL 60439

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Apparatus to Measure Liquid Helium Boil-off from Low-loss Superconducting Current Leads

Y. S. Cha, R. C. Niemann, and J. R. Hull

Energy Technology Division, Argonne National Laboratory, Argonne,
IL 60439

A low-loss liquid helium dewar was constructed to measure the liquid helium boil-off rate from high-temperature superconducting current leads. The dewar has a measured background heat leakage rate of 12 mW. Equations calculating the heat leakage rate from the measured vapor mass flow rate in liquid helium boil-off experiments are derived. Parameters that affect the experiments, such as density ratio, absolute pressure, and rate of pressure variation, are discussed.

I. INTRODUCTION

One of the earliest applications of bulk high-temperature superconductors is in current leads for low-temperature superconducting devices. The incorporation of high-temperature superconductors into current leads connecting ambient-to-cryogenic temperatures provides the opportunity to significantly reduce heat input from the lead and thus reduce cryogen usage and/or refrigeration power.¹⁻⁴ Currently, there are projects going on in the United States that are aimed at incorporating the high-temperature superconducting current leads in superconducting magnetic energy storage (SMES) systems.⁴ One of the project is considering using the high-temperature superconducting current leads in a micro-SMES (0.3-kWh) device for power-quality applications. Another project is considering using the high-temperature superconducting current

leads in a mid-sized SMES (0.5-MWh) system. The high-temperature superconductor current leads have much lower heat leakage rate than conventional copper leads because (1) the thermal conductivity of the ceramic superconductor is lower than that of the copper, and (2) joule heating in the superconductor is negligible compared to that of the copper. To measure the relatively low heat leakage rate (1-100 mW) of the current leads we need a dewar which has a background heat leakage rate from the environment comparable or lower than the heat leakage of the current leads. At such low heat leakage rates, a small disturbance in the environment could cause significant error in the measurement. In this paper, we describe the characteristics of a low-loss liquid helium dewar designed specifically for measuring the heat leakage rate of a pair of high-temperature superconducting current leads. We will derive the equations used to calculate the heat leakage rate from the measured vapor mass flow and discuss the important parameters that affect the measurement of the heat leakage rate.

In addition to measuring heat leakage rate of high-temperature superconductor current leads,^{4,6} there are other applications for liquid helium boil-off experiments. It has been used to determine the a.c. loss of superconductors⁷ and to measure the thermal conductivity of insulating materials.⁸ Liquid helium is particularly suitable for calorimetric measurement because it has the lowest latent heat of vaporization among all the cryogenics. This property of liquid helium becomes even more important when relatively small rate of heat loss is being measured because more helium is boiled off than any other cryogenics for the same heating rate. Higher accuracy can be achieved by using liquid helium since

the problem of measuring extremely low mass flow rate can be avoided. Similarly, lower heat loss rate, which are difficult to measure using other cryogenics, can be measured by using liquid helium. Another reason for using liquid helium is that it is the only cryogen suitable for low temperature superconducting devices.

II. A LOW-LOSS LIQUID HELIUM DEWAR

We have designed and built a low-loss liquid helium dewar in our laboratory to measure the heat leakage rate down a pair of high-temperature superconductor current leads. Figure 1 shows the schematic of the low-loss liquid helium dewar. The dewar consists of an inner liquid-helium reservoir within an outer liquid-helium reservoir that is thermally shielded from the room-temperature environment by multiple insulation layers in a vacuum environment and a liquid nitrogen reservoir. The inner helium reservoir has a copper heat intercept to minimize radiative, conductive and convective heat transfer to the liquid helium in the lower portion of the reservoir. The lower portion of the inner reservoir below the copper heat intercept is filled with liquid helium and is where boil-off occurs. The upper portion of the inner reservoir above the copper heat intercept is filled with vapor and several thermal baffles are placed there to reduce radiative heat transfer to the lower portion of the inner reservoir and to reduce natural convection in the vapor space. There is an insulating vacuum between the inner helium reservoir and the outer helium reservoir to reduce thermal interactions between the two helium reservoirs. All the reservoirs are made of thin-walled stainless steel. The

dewar is 1.143 m high and the inner helium reservoir has an inside diameter of 0.216 m. The outer helium reservoir has an inside diameter 0.330 m. Also shown in Fig. 1 is a part of a cryocooler system used to intercept heat from the upper stage (conventional copper leads) of the lead assembly. Thermal interaction between the two helium reservoirs of the present dewar is much less than that of a previously reported dewar⁴ used to measure the heat leakage rate of high-temperature superconductor current leads. This is because the vacuum space between the two helium reservoirs of the previously reported dewar did not extend all the way to the top of the dewar. A small perturbation in the outer reservoir quickly causes a drastic change in the inner reservoir (and vice versa) and subsequently a long period is needed to reach the new steady-state. More detailed comparison of the two dewars are described in reference 9.

III. EXPERIMENTAL RESULTS

A. Background Heat Leakage Rate

A typical test to measure background heat leakage rate is shown in Fig. 2. The measured mass flow rate drops sharply during the initial cool down period. After approximately five hours, the rate of change of the vapor flow rate becomes much smaller. But, steady-state is not approached until 20 hours later where the measured vapor flow rate changed very little. As long as the liquid level in the outer helium reservoir is above the copper heat intercept, the heat transferred to the lower portion of the inner helium reservoir can be kept at constant and relatively low values.

During these background heat leak measurements, the liquid level in the outer helium reservoir was kept above the copper heat intercept by continuously transferring liquid helium into the outer reservoir. Test results show that the steady-state heat leak in the inner helium reservoir is independent of the liquid helium level in the outer reservoir when it is above the copper heat intercept. The heat leakage rate, however, does dependent on the liquid level in the inner helium reservoir as shown in Fig. 3. The heat leakage rate increases with the helium level in the inner reservoir. When the liquid helium level in the inner reservoir dropped below 40%, the heat leakage rate becomes quite insensitive to the liquid helium level and the heat leakage rate approaches 12 mW, which is sufficiently small compared to the expected heat leakage rate from the high-temperature superconductor current leads at relatively low currents.

B. Heat Leakage Rate of BSCCO Current Leads

We have performed measurements of heat leakage rates of a pair of high-temperature superconductor current leads made from sinter-forged BSSCO 2223 under both DC and AC conditions.¹⁰ Figure 4 shows the variation of the total heat leakage rate with current. The total heat leakage rate is calculated from the measured vapor mass flow rate and includes both the background heat leakage rate and the heat leakage rate through the high-temperature superconductor current leads. Subtracting the background heat leakage rate (Fig. 3) from the total heat leakage rate (Fig. 4) gives the heat leakage rate through the high-temperature superconductor current leads only and the results are shown in Fig. 5. At low currents, the background heat leakage rate is a significant portion of

the total heat leakage rate. As the current increases, the heat conducted down the leads increases correspondingly and the background heat leakage rate becomes only a small fraction of the total heat leakage rate. The heat leakage rates shown in Fig. 4 or 5 are much smaller than that of conventional copper leads. The data in Fig. 4 (for two leads) shows that at a DC current of 100 A, the total heat leakage rate for the BSCCO lead is 29 mW per lead. The heat leakage rate for copper lead at 100 A is approximately 100 mW. Thus, the heat leakage rate of the BSCCO lead is 29% of that of the conventional copper lead. The heat leakage rate of high-temperature superconductor current leads can be further reduced if an intermediate heat intercept is provided at the junctions between the upper stage copper leads and the lower stage high-temperature superconductor leads.¹⁰

IV. MEASUREMENT ANALYSIS AND DISCUSSIONS

The heat leakage rate described previously is calculated from the measured vapor mass flow rate. As we shall demonstrate later, the conventional way of calculating the heat leakage rate of multiplying the latent heat of evaporation of liquid helium by the measured vapor mass flow rate is not adequate and significant errors can be introduced. We shall derive the appropriate equation first and then discuss the effect of various parameters on the helium boil-off experiments.

A. Analysis

A typical helium calorimetric experiment consists of primarily an insulated helium dewar and a mass flowmeter as shown in Fig. 6. The dewar usually can store a sufficient amount of liquid helium so that the experiment can last over an extended period of time. We define a control volume which includes all the liquid helium in the dewar. The system boundary, therefore, consists of the interface between the liquid and vapor, and the interface between the liquid and inside walls of the dewar. It is assumed that equilibrium exists between the liquid and the vapor at the interface so that all the properties can be evaluated at the saturation condition. We further assume that equilibrium exists within liquid and vapor itself. The effect of variation of hydrostatic pressure in the liquid is assumed to be small. In the following, we shall provide a relatively simple derivation of a equation which is used to calculate the heat leakage rate from the measured vapor mass flow rate. The derivation is based on the assumption that the system pressure is constant. We shall address the effect of pressure variation in a later section.

During a small time interval Δt , a small amount of liquid Δm_f is evaporated. The majority of the evaporated liquid escapes through the top of the dewar while a small portion of the evaporated liquid remains in the control volume to fill the space vacated by the evaporated liquid. Conservation of mass gives

$$-dm_f/dt = dm/dt + dm_g/dt , \quad (1)$$

where dm_g/dt is the rate of change of vapor mass in the control volume, and dm_f/dt is the rate of change of liquid mass in the control volume. The heat leak rate is

$$dQ/dt = -h_{fg}(dm_f/dt) . \quad (2)$$

The rate of decrease in liquid space (V_f) must equal to the rate of increase in vapor space (V_g) in the control volume

$$dV_g/dt = -dV_f/dt . \quad (3)$$

If we assume that the pressure remains constant, then

$$\rho_g(dV_g/dt) = dm_g/dt ; \quad \text{and} \quad \rho_f(dV_f/dt) = dm_f/dt, \quad (4)$$

Substituting Eq. 4 into Eq. 3,

$$dm_g/dt = -(\rho_g/\rho_f)(dm_f/dt) . \quad (5)$$

Substituting Eq. 5 into Eq. 1, and solve for dm_f/dt ,

$$dm_f/dt = (dm/dt)/(\rho_g/\rho_f - 1) . \quad (6)$$

Eliminating dm_f/dt from Eqs. 2 and 6 results in

$$dQ/dt = h_{fg}(dm/dt)/(1 - \rho_g/\rho_f). \quad (7)$$

For a given system pressure, the equilibrium properties h_{fg} , ρ_g , and ρ_f can be determined, then the heat leakage rate is calculated by Eq. 7 using the measured vapor mass flow rate. If a density correction factor is defined

$$F_c = 1/(1 - \rho_g/\rho_f), \quad (8)$$

then Eq. 7 becomes

$$dQ/dt = F_c h_{fg} (dm/dt). \quad (9)$$

B. Effect of Density Ratio

It is clear from Eq. 7 that not only the latent heat but also the density ratio are needed to calculate the heat leakage rate. Figure 7 shows the variation of the density correction factor F_c with the normalized system pressure (P is absolute pressure of the system and P_0 is equal to one atmospheric pressure). At one atmospheric pressure ($P/P_0=1$), F_c is about 1.15, which is a 15% correction. The reason that the density correction is significant is because the density of helium vapor is not negligibly small compared to that of liquid helium near or above one atmospheric pressure. F_c increase substantially with pressure. This correction factor arises because during a small time interval dt , a small amount of vapor appears in the control volume. The total amount of vapor generated by the heat dQ during the time interval dt is equal to the sum of the vapor leaving the control volume and the vapor remaining in the control volume. Thus, dQ/dt will always be larger than that calculated by multiplying h_{fg} by dm/dt and the difference is given by Eq. 8. This density correction has

been known for sometime,^{11,12} but it was originally derived for liquids other than cryogenics. Furthermore, this density correction is negligible for all the cryogenics except helium. This is probably the reason why most recently reported helium boil off experiments⁶⁻⁸ have not taken this effect into account.

C. Effect of Absolute Pressure

Figure 7 also shows the effect of system pressure on the latent heat of vaporization. The latent heat of evaporation decreases sharply with pressure near one atmospheric pressure which is opposite to that of the density correction factor F_c . Equation 7 or 9 can be rewritten as

$$dQ/dt = (F_c h_{fg}/h_{fg,0}) h_{fg,0} (dm/dt). \quad (10)$$

Since $h_{fg,0}$ is the latent heat of evaporation at one atmospheric pressure and is a constant (20.42 kJ/kg), the overall effect of pressure is contained in the dimensionless parameter $F_c h_{fg}/h_{fg,0}$. Figure 8 shows the variation of this dimensionless parameter with the normalized pressure. At one atmospheric pressure, $F_c h_{fg}/h_{fg,0}$ has a value of 1.15. Either Eq. 9 with Fig. 7 or Eq. 10 with Fig. 8 can be used to calculate the heat leakage rate from the measured vapor mass flow rate.

D. Effect of Pressure Variation

Equations 9 and 10 are derived under the assumptions of constant pressure and thermodynamic equilibrium between liquid/vapor interface,

as well as equilibrium within each phase. If pressure changes somewhat over an interval, the boil-off will be either suppressed or enhanced depending on whether the pressure is increased or decreased. An equation derived based on an approximate thermodynamic analysis can be used to evaluate the heat leakage rate¹³

$$dQ/dt = h_{fg}(dm/dt)/(1 - \rho_g/\rho_f) + (m_f C_v T v_{fg}/h_{fg})dP/dt \quad (11)$$

where m_f is the mass of the liquid helium in the dewar, C_v is the specific heat of liquid helium at constant volume, T is the saturation temperature, and $v_{fg} = v_g - v_f$; v_g and v_f are the specific volume of the vapor and liquid, respectively. The second term on the right hand side of Eq. 11 is the contribution due to pressure variation. It depends not only on the properties of helium but also on the liquid helium inventory in the dewar. To reduce the effect of pressure variation, one can either actively control the system pressure or reduce the liquid helium inventory in the dewar.

E. Effect of Non-equilibrium

If thermodynamic equilibria do not exist in the liquid and vapor in the system, errors will be introduced in the calculation of the heat leakage rate from the measured vapor mass flow rate. In order to have thermodynamic equilibria, both the volumes occupied by the liquid and the vapor should be sufficiently small. Otherwise, internal convections (particularly in the vapor space) may occur which makes the interpretation of the experimental result more precarious. Under such

circumstances, one need to carry out the analysis to determine the pattern of natural convection which is strongly geometry dependent.

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Figure Captions

- Fig. 1 Schematic diagram of a low-loss liquid helium dewar.
- Fig. 2 Time history of measured vapor mass flow and liquid helium level in inner reservoir of the low-loss liquid helium dewar.
- Fig. 3 Variation of background heat leakage rate with liquid helium level in inner helium reservoir.
- Fig. 4 Variation of total heat leakage rate with current .
- Fig. 5 Variation of heat leakage rate through the BSCCO superconductor leads with current.
- Fig. 6 Schematic of a typical helium calorimetric apparatus and the control volume used in the analysis.
- Fig. 7 Variations of the density correction factor F_c and the normalized latent heat with normalized pressure.
- Fig. 8 Variation of the dimensionless parameter $F_c(h_{fg}/h_{fg,0})$ with normalized pressure.

Fig. 1

Fig. 3

Fig. 5

Fig. 7

Fig. 8