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FORCED TWO PHASE HELIUM COOLING OF LARGE
SUPERCONDUCTING MAGNETS

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ABSTRACT

A major problem shared by all large superconducting magnets is the cryogenic cooling system. Most large magnets are cooled by some variation of the helium bath. Helium bath cooling becomes more and more troublesome as the size of the magnet grows and as geometric constraints come into play. An alternative approach to cooling large magnet systems is the forced flow, two phase helium system.

This report shows the advantages of two phase cooling in many magnet systems. The design of a two phase helium system, with its control dewar, is presented. The paper discusses pressure drop of a two phase system, stability of a two phase system and the method of cool down of a two phase system. The results of experimental measurements at LBL are discussed. Included in this discussion are the results of cool down and operation of superconducting solenoids.

INTRODUCTION

A major problem with all large superconducting magnets is the cryogenic and refrigeration system. Almost all of the large magnets are cryogenically stabilized. They are cooled in a bath of boiling helium. Nucleate boiling in liquid helium permits heat fluxes of 3000Wm^{-2} to be transferred with a temperature drop of less than 0.5K. The bath-cooled magnet is difficult to cool from room temperature to 4K. Helium, which is a difficult fluid to use as a coolant because of its low atomic weight, must flow into each region of the magnet; if the flow in a section of the magnet is restricted, stratification occurs and that magnet section remains warm.

Once the pool-boiled magnet is cold and the cryostat is filled with liquid helium, the refrigeration problems are not over. Helium has a very low heat of vaporization (20Jg^{-1} at 4.2K).^[1] As a result, the release of large quantities of magnet-stored energy during a quench (even cryo-stable magnets quench on occasion) will result in large quantities of helium gas being flashed. For example, 1MJ of energy will boil 400 liquid liters of helium into 286m^3 ($10,000\text{ft}^3$) of helium gas at STP. The large amount of helium gas generated by a quench requires careful design of the inner cryostat vessel and the relief valve system. The thickness of a large diameter pressure vessel which is designed for at least 3atm is not trivial.

Large superconducting magnets don't have to be bath cooled in many cases. Intrinsically stable superconductor does not care how it is cooled as long as it is kept below its critical temperature. Bath cooling, with liquid helium in direct contact with the superconductor, is undesirable in any magnet which is designed so that it can quench. The helium in direct contact with the superconductor restricts the growth of the propagating

normal region, which makes burnout of the coil more likely. The helium cooling in an intrinsically stable coil should be away from the superconductor. A forced flow helium tubular cooling system will provide all of the cooling that is needed. This system will also avoid all of the major problems which are encountered in any large cryogenic system. The advantages of the tubular cooling over an ordinary bath cooled system are:

- 1) The cooldown of the magnet is well controlled because the helium flows in a well defined path.
- 2) The mass of the tubular cooling system is less than that of a helium bath cryostat.
- 3) The amount of helium in direct contact with the magnet coil is minimized. Helium boil-off during a quench is orderly and well controlled. Cryogenic safety in such a system is greatly enhanced.
- 4) Tubular cooling is unaffected by magnetic forces. A bath cooled superconducting magnet in space is vulnerable to diamagnetic repulsion; a tubular cooled system is not.

The tubular cooling system is not new, a number of superconducting magnets use this system. [2,3,4,5] The Lawrence Berkeley Laboratory system is different because it employs two phase helium instead of supercritical helium (the critical pressure of helium is $2.25 \times 10^5 \text{ Pa}$; the critical temperature for helium is 5.19K). The reasons for choosing two phase helium over supercritical helium are:

- 1) A two phase "boiling" helium system will operate at lower temperatures than a supercritical helium system. A lower operating temperature allows the superconductor to carry more current.
- 2) The mass flow required in the cooling circuit for a given amount of refrigeration is lower for a two phase system than for a supercritical system. In most cases the pressure drop will be lower as well.

- 3) Boiling two phase helium can transfer large local heat fluxes without changing the temperature of the stream.

Two phase helium forced cooling is, in most cases, superior to supercritical cooling. There are instances when this is not true, they are when: 1) the dielectric strength of the helium must be uniform, (for example in superconducting transmission lines); 2) the pressure drops in the system must be above 5×10^4 Pa; and 3) the operating temperature range includes temperatures above 5.2K.

DESIGN OF A TWO PHASE COOLING SYSTEM

The most important consideration in design of two phase flow systems (this applies to other systems as well), is the elimination of parallel paths. The most desirable system is the simple series flow system. A series flow system has almost no control problems; therefore, no additional refrigeration is expended to control the flow. When a parallel flow system cannot be avoided, one should strive to minimize the number of parallel flow circuits. Each parallel circuit should have its own control dewar system. The principle of the control dewar will be discussed later in this report.

There are two other important considerations when one designs a two phase helium flow system. They are low pressure drop and flow stability. The former is achieved by choosing an appropriate length to diameter ratio and the latter is achieved by choosing an appropriate operating regime. The two unfortunately, go hand in hand. There is however, wide latitude in choosing tube diameter and tube length.

In general, one wants to operate on the liquid side of the two phase liquid vapor dome. One also wants to operate in the bubble and froth regime of the Baker^[6] diagram. (In general one would like to operate the system and mass flows per unit area of greater than $10\text{kg s}^{-1}\text{m}^{-2}$, which keeps one out of the slug and plug flow regime.)^[7]

A) TWO PHASE PRESSURE DROP

A series of pressure drop calculations were done using the Martinelli Nelson Technique.^[8] Although the calculations agreed with experiments, they turned out to be a waste of time. The much simpler equation given below yielded almost the same results for round tubes (the reason for this is that the density change across the two phase dome is less than a factor of 8).

$$\Delta P = \frac{8}{\pi^2} \frac{m^2}{\rho} \left[1 + \frac{fz}{D} \right] \frac{1}{D^4} \quad -1-$$

where

$$f = 0.184 \text{Re}^{-0.2} \text{ (turbulent flow smooth pipes)} \quad -1a-$$

$$\text{Re} = \frac{4m}{\pi D \mu} \quad -1b-$$

and where m is the mass flow (kg s^{-1}), ρ is the average density of the exiting helium (kg m^{-3}); z is the tube length (m); D is the tube diameter (m); μ is the helium gas phase viscosity ($\text{kg s}^{-1} \text{m}^{-1}$; note that $1 \text{ kg s}^{-1} \text{m}^{-1} = 10$ poise); and ΔP is the pressure drop along the tube (Nm^{-2} or Pa); (note that $1 \text{ bar} = 10^5 \text{ Pa} = 14.55 \text{ psi}$).

In order to achieve low pressure drop, one wants to maximize the density of helium in the cooling tube. For that reason, our systems are designed to operate so that liquid helium which circulates has the lowest quality X . (Quality, in our case, is defined in the same sense as it is for steam. A quality of 0 is saturated liquid; a quality of 1 is saturated vapor. Qualities between 0 and 1 define where the fluid is in the two phase region.) Quality X is defined as follows:

$$X = \frac{H - H_g}{H_g - H_l} = \frac{S - S_g}{S_g - S_l} = \frac{V - V_g}{V_g - V_l} \quad -2-$$

Where H , S and V are enthalpy, entropy and specific volume, the subscript l denotes saturated liquid; the subscript g denotes saturated vapor; and no subscript denotes the two phase region. H , S and V are bounded by the liquid vapor dome so that the quality X is always between zero and one ($0 \leq x \leq 1$). Once V , the two phase specific volume is known, the density of the two phase fluid can be found by taking the reciprocal of V . The reduction of quality in the flow system not only reduces the pressure drop. As a result, the operating temperature is reduced and the temperature change across the system is minimized.

B) THE HELIUM CONTROL DEWAR AND COOL DEWAR CIRCUIT

Two kinds of systems can be used to circulate low quality helium through the magnet cooling tube, they are: 1) a liquid helium pump used as a circulator or, 2) the refrigerator compressors used as a circulator. Both systems use a heat exchanger to insure that the helium will enter the system at or near the saturated liquid line. Figure 1 shows schematic diagrams of the two approaches.

The helium pump loop system shown in Figure 1a has the following advantages: 1) The refrigerator is completely decoupled from the load. In theory, one could substitute liquid helium from a storage dewar for the refrigerator. 2) The mass flow through the system is limited by the capacity of the pump, not the capacity of the refrigerator. The two disadvantages of the use of a helium pump system are: 1) the pump work is put into the helium and therefore extra refrigeration must be supplied to overcome the work which goes into pumping; 2) the simple pump loop system shown in Figure 1a cannot be used to cool the magnet down from room temperature; one should connect the magnet cooling system directly to a refrigerator.

The refrigerator compressor can be used as a circulator provided a heat exchanger is used in an accumulator. The function of this heat

exchanger is to reduce the inlet quality to the magnet cooling tube. The quality change across the magnet remains the same for a given mass flow in the circuit. The circuit shown in Figure 1b has two Joule Thompson valves (J-T valves) which expand the gas in two stages. The first J-T valve expands from 15-18 bar to 3 bar. The heat is transferred to the boiling liquid helium in the accumulator tank as the gas flows through the heat exchanger. Expansion of the gas from 3 bar to the final inlet pressure of the load will result in an inlet quality at the load which approaches zero. If there were no heat exchanger the inlet quality at the load would be around 0.4; the pressure drop in the tubular cooling system would be a factor of 2 to 3 higher.

The system shown in Figure 1b is analyzed from a thermodynamic standpoint in reference [9]. This system is capable of being operated at 40-60 percent over the capacity of the refrigerator for short periods of time. (The amount of time is dependent on the amount of excess liquid helium in the accumulator). It can be cooled down by the refrigerator directly, provided one bypasses the gas back to the compressors after that gas has passed through the load being cooled down from room temperature. Figure 2 shows how the system shown in Figure 1b can be hooked into a system to cool a magnet down, operate the magnet, and warm the magnet back up to room temperature.

Figure 2 is highly schematic, but it shows the essence of the LBL control dewar system which can be located remotely from the load being cooled. A hybrid system which uses both a helium pump and the refrigerator compressors as circulators has been built to cool the TPC magnet.[10] This system is redundant, so that the magnet can be operated whether or not the refrigerator operates. (The helium pump circulates stored liquid while the refrigerator is being repaired.) If the helium pump is inoperable but

there is a refrigerator, the forced flow through the coil is supplied by the refrigerator itself.

C) THE GARDEN HOSE EFFECT

Large superconducting magnets, which are force cooled with two phase helium, may face an additional problem which depends on the orientation of the cooling circuit. If the magnet cooling circuit is oriented so that the two phase flow is horizontal or near horizontal, the two phase flow should be stable and it should have a pressure drop which is predictable using Equation 1. If the two phase flow is vertical with many up and down loops, the flow is subject to the so called "garden hose" pressure drop and "garden hose" oscillation.

Garden hose pressure drop and oscillations are not fully understood, but they have been observed experimentally. The garden hose pressure drop can be visualized by looking at a garden hose which is half full of water and hangs in a coil on a peg. It takes a great deal of pressure to force the water out of the hose due to the additive effect of the various heads of water in each of the coils. A similar behavior has been noted in helium systems even though the flow is presumed to be in the bubble and froth regime of the Baker diagram.

Garden hose pressure drop can be estimated roughly using the following expression for a coil of N round loops, of major diameter D, which have an axis orientation angle of Θ from the horizontal.

$$\Delta P^* = 0.2 N D a \left(\rho_l - \rho_g \right) \cos \Theta \quad -3-$$

where P^* is the pressure drop due to the garden hose effect; ρ_l is the density of the helium liquid phase; and ρ_g is the density of the helium gas phase; a is the acceleration of gravity. The coefficient 0.2 is derived from our experimental measurements of garden hose pressure drop and is

probably related to the velocity of the coolant. At best, equation 3 can only be regarded as an approximation. ΔP^* is added to the pressure drop ΔP which is calculated in equation 1.

From equation 3, it appears that garden hose pressure drop will decrease as the system approaches the critical pressure because $\rho_g - \rho_l$ is reduced as one approaches the critical pressure. The other obvious limitation is that ΔP^* is less than the difference between the critical pressure and the system exit pressure regardless of what the value of N and D are. A reduction of the ND product will reduce garden hose pressure drop. Changing the axis of the hoops from horizontal ($\theta=0$) to vertical ($\theta=90^\circ$) will eliminate ΔP^* entirely.

Garden hose oscillation is probably caused by a change in flow regime from bubble and froth to slug and plug. Starting and stopping the flow requires the flow to cross over the slug and plug flow regime. The oscillatory behavior of slug and plug flow, coupled with various spring constants of the system, which includes the refrigerator or pump loop, probably contributes to the oscillation. The amplitude of the pressure pulse due to garden hose oscillation appears to be no greater than the garden hose pressure drop ΔP^* .

D) GAS COOLED ELECTRICAL LEADS

Gas cooled electrical leads present no problem on a forced cooled two phase helium. First, one can take two phase helium directly from the cooling system without any ill effect to the magnet, the leads, or the cooling circuit. No additional lead pot is necessary. Second, the superconducting leads from the magnet do not have to be in liquid helium. They only have to be in contact with the refrigeration supplied by liquid helium.

The implications of the two previous points permit one to design magnets that have the electrical leads brought out into the vacuum space

and attached to a pipe or bus bar cooled by liquid helium. The high voltage arcing, which is a common fault in large magnets, can be eliminated. Therefore, quench protection voltages up to 5kV are relatively easy to handle. A second implication is that installation and assembly can be simplified.

The design of the electrical lead itself is not changed by the fact that it runs off of a two phase cooling system. However, one must remember that lead operation on a refrigerator is different from operation in a bath of helium without a refrigerator. (This statement is true for bath cooled magnets as well as force cooled magnets.) The precautions one must take with gas cooled leads which run off a forced flow system are: 1) the leads should be oriented so that the warm end is above the cold end, and 2) the flow of gas through the leads must be controlled so that the leads do not run hot. One may use a controller which measures lead temperature or one may measure the voltage drop across the electrical lead.

EXPERIMENTAL MEASUREMENTS

The LBL group has operated three large test superconducting magnets using a two phase tubular cooling system. Most of the early work was done using a modified version of the circulation system shown in Figure 1B.[11,12] Tests were done in the summer of 1979 using a helium pump.

A) SOLENOID TESTS ON A REFRIGERATOR

Two 1-meter diameter test solenoids and one 2-meter diameter test solenoid were cooled by two phase helium and were operated at or near critical current at temperatures from 4.6 to 4.8K. The two 1-meter solenoids were operated in series. The cooling circuit tubes are shown in Figure 3. The circuit length was 235m; the cooling tube ID was 10.8mm.

were a total of 72 turns of cooling tube 1m in diameter. The axis of the two coils in series was vertical ($\theta = 90^\circ$). The 2-meter test coil

contains 365m of 10.8mm ID tube wound in 55 turns which are 2-meters in diameter. During the test the coil axis was vertical. The 2-meter diameter solenoid is shown in Figure 4.

The cooldown of both tests took a bit over one day when a CTi Model 1400 refrigerator was used. Figure 5 shows the pressure drop in the cooling circuit as the two 1-meter diameter solenoids cooled down. The onset of two phase flow in the tube was signaled by a sudden drop in the pressure drop across the circuit. Since the cooling circuit axis was vertical, no garden hose pressure drop or oscillation was observed. There was no oscillatory behavior observed in temperature or pressure. Changes in pressure drop were gradual. The more liquid in the accumulator, the lower the pressure drop was. The temperature corresponded to the saturation temperature which was controlled by the absolute pressure in the tube. The 2-meter test coil behaved as well as the 1-meter test coils. There were pressure drops during two phase flow of less than 10^4 Pa and there was no oscillatory behavior. At 4.6K the CTi 1400 refrigerator supplied two phase helium to the experiment at the rate of 4gs^{-1} .

The gas cooled electrical lead performed just as they would in a bath of helium. Liquid entering the bottom of the gas cooled leads had no effect on their performance. Gas flow through the electrical lead was regulated with a needle valve just upstream from a Rotometer type gas flow meter.

B) GARDEN HOSE TESTS

The garden hose effect was tested with a separate experiment, detailed data can be found in reference [13]. Later the garden hose test coil was mounted in series with the 2-meter diameter test coil, in order to test the effect of garden hose pressure drop oscillations on a superconducting magnet.

The garden hose test coil was made with 160 turns of 16.6mm ID tube. The diameter of each turn was 0.9m. The tube was divided into two bundles of 80 turns each. Pressure taps and carbon resistor temperature sensors were installed at the ends of the two circuit and at a center tap between the two bundles. Pressure was measured by room temperature transducers. The test coil was run on the CTi 1400 refrigerator at two phase helium mass flows as high as $4\text{-}5\text{gs}^{-1}$.

The measured garden hose pressure drop was about $2 \times 10^4\text{Pa}$ ($2.4 \times 10^4\text{Pa}$ is predicted using equation 3). In addition, a pressure oscillation with a period of about 30 seconds was seen. (Short chops of higher frequency were seen, but the 30 second period was consistently seen.) The peak to valley amplitude of this oscillation was around $2 \times 10^4\text{Pa}$. Oscillations seen at one pressure tap did not correlate well with oscillations seen at other taps. Temperatures tended to correlate with absolute pressure (except at the entry of the experiment).

Several observations can be made about the experimental data: 1) the garden hose pressure drop and the oscillation amplitude decreased as the pressure rose, the garden hose effect ceased at or near the critical point; 2) garden hose oscillation frequency did not vary a great deal with either pressure or mass flow; 3) other much longer period oscillations (about 30 minutes) were seen when the control dewar was empty and the existence of two phase flow was in doubt.

C) HELIUM PUMP LOOP TESTS

A reciprocating double acting bellows type helium pump was built and tested at LBL. The pump is driven by a torque motor at room temperature; the reciprocating motion is transmitted to the pump (which is at 4K) through a shaft which operates between room temperature and 4K. The helium pump is connected to a copper tube heat exchanger which has an area

of about 2-square meters. This heat exchanger removes most of the pump work from the pumped helium stream. The helium pump and its heat exchanger are shown in Figure 6. More data on the LBL helium pump is reported in reference [14].

The LBL helium pump was first tested in its dewar without the external transfer lines connected. We were able to measure volumetric efficiency as a function of torque motor speed, stroke and pressure across the pump. In general, the highest volumetric efficiencies were found at the highest speeds and lowest pressure rise across the pump. At a mass flow of 27gs^{-1} and a pressure rise of about $4 \times 10^4\text{Pa}$, we observed volumetric efficiencies as high as 80 percent. At lower pressure rises, we observed volumetric efficiencies of 90 percent or more. The pump is capable of delivering about 50gs^{-1} but we did not measure volumetric efficiencies at mass flows greater than 27gs^{-1} . At low mass flows the volumetric efficiency dropped below 50 percent. We believe that late closing of one of the poppet inlet valves at the lower speeds is responsible for the decline of volumetric efficiency.

The helium pump was tested in conjunction with the TPC magnet control dewar and transfer lines. The pump was run at mass flow rates of about 8gs^{-1} and 40gs^{-1} . The control dewar was refrigerated by a CTi Model 1400 refrigerator and the pump was run when there was no refrigeration. At the highest mass flow (40gs^{-1}), the calculated adiabatic efficiency was around 50 percent. At the lower mass flow rate (8gs^{-1}), the adiabatic efficiency appeared to drop to about 30 percent. The measurements are consistent with the decline in volumetric efficiency which occurs at low pump mass flow.

CONCLUSIONS

The two phase force cooled system is desirable for many kinds of superconducting magnet systems to be used in accelerators, particle physics and in space. Two phase cooling systems are often lower cost than conventional bath systems. LBL has demonstrated that forced two phase cooling works very well in large diameter thin solenoid magnets. Two phase flow systems can be designed so tht they are a reliable way of cooling superconducting magnets at temperatures approaching that of a bath cryostat. The two key elements in the design of two phase flow systems is the elimination of parallel circuits and the minimization of the number of up and down loops which can cause garden hose oscillation and pressure drop.

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(LEGEND)

—	Lines carrying flow.		Open full flow valve.
- - -	Lines not carrying flow.		Closed J-T valve.
	Closed full flow valve.		Open J-T valve.

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