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Title: Comparing Supercritical Cooling and Pool Boiling For a Superconducting System Using RHIC Parameters and Features

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Comparing Supercritical Cooling and Pool Boiling for a Superconducting System using RHIC Parameters and Features

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The thermodynamic efficiency of Supercritical Cooling and Pool Boiling has been studied using RHIC as an example. The calculated compressor power for Supercritical Cooling is about 11 % more than that of a hypothetical Pool Boiling system (assuming one can actually make it work). A brief review of the RHIC design shows significant advantages of Supercritical Cooling and limitations with Pool Boiling. There is no doubt that Supercritical Cooling is the right choice for RHIC, and the RHIC type cooling could be a good choice for future projects with similar features.

INTRODUCTION

It is difficult to compare cooling schemes for superconducting systems. On paper, keeping the superconducting device in a liquid helium bath is the simplest method. In real applications, magnets must be connected in series over long distances and Supercritical Cooling is often used. The intention of this study is not to investigate and compare various cooling schemes but to compare the thermodynamic efficiency of a Supercritical Cooling system using Pool Boiling as the reference system. Thus the advantage of Supercritical Cooling can be compared explicitly with the associated power penalty.

Most of the time, the cooling system for a superconducting project is selected based on magnet design, system layout and operating needs. Efficiency of cryogenic plant, hardware, cost and reliability are considered in the design phase. In general, Supercritical Cooling needs more equipment than Pool Boiling, and inherits penalties on efficiency. Cost and reliability are arguable. Power penalty and unfavorable features must be justified by the need. Among the several Supercritical Cooling schemes, the present study addresses only the scheme using a cold circulating compressor and only considers the thermodynamic efficiency. Cost and reliability are not addressed at this stage to avoid confusion.

COOLING SCHEMES

As shown in Figure 1, a superconducting magnet is cooled by supercritical helium in a closed loop. A cold circulating compressor is used to provide supercritical helium at approximately 5 atm with a flow (100 g/s for example) through a heat exchanger in the liquid helium bath. In the helium bath, supercritical helium is cooled slightly below the magnet temperature. For comparison purposes, a similar magnet cooled by Pool Boiling is shown in Figure 2. The heat load Q and temperature T for the two magnets are assumed to be the same. To simplify the comparison, there is no lead flow in either system. The load of the cryogenic system is 100% refrigeration and 0% liquefaction.

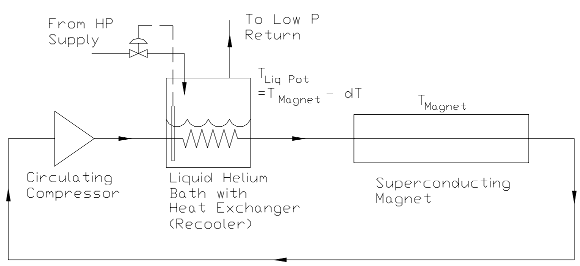

Figure 1. Supercritical cooling using cold circulating compressor.

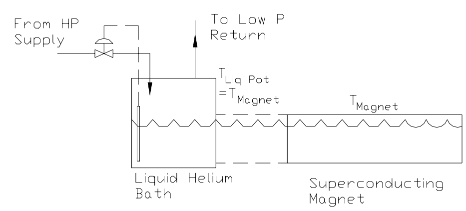

Figure 2. Pool boiling cooling.

HELIUM REFRIGERATOR AND INPUT POWER

For Supercritical Cooling using a circulating compressor, there is a heat input W from pump work. The liquid helium bath also needs to be operated at a slightly lower temperature in order to keep the magnet at the same temperature as that in Pool Boiling. Thus the load of the helium refrigerator is (Q + W) at temperature (T – dT) for Supercritical Cooling, and is Q at temperature T for Pool Boiling.

As one can see, the efficiency of Supercritical Cooling depends on the magnitude of the pump work and the temperature difference. It approaches that of Pool Boiling if the pump work and the temperature difference are small. On the contrary, Supercritical Cooling is not efficient if W/Q or dT is non-negligible.

The pump work W and the temperature difference dT are determined by system design and detailed engineering. Both depend on such parameters as: efficiency of the circulating compressor, flow rate, flow area, length, heat load, allowable temperature variations in the magnet, number of recoolers and piping layout, etc. No universal values can be given. A reasonable comparison can be carried out using parameters obtained from an operating facility such as RHIC.

In the RHIC baseline design, the 4.5 K refrigeration heat load is 5.8 kW and the pump work is 125 W. The design pump work accounts for 2.2% of the 4.5 K refrigeration load. The actual heat load of RHIC are slightly higher. The unofficial heat load from the magnet system is about 8 kW and the pump work equals approximately 200 W. The actual pump work accounts for roughly 2.5 % of the refrigeration load. In RHIC, the temperature in the recooler is 4.25 K for 4.60 K maximum magnet temperature. In principle, a 4.60 K refrigerator could be used for the hypothetical Pool Boiling scheme. The Supercritical Cooling needs a 4.25 K refrigerator. Using identical Carnot efficiencies for these two refrigerators, the 4.25 K refrigerator requires 4.60 / 4.25 ~ 1.08 (or 8%) more input power than the 4.60 K refrigerator. Thus the overall thermal efficiency penalty is about 11 % for the RHIC Supercritical Cooling scheme using cold circulating compressor compared with the hypothetical Pool Boiling Scheme.

ADVANTAGES OF SUPERCRITICAL COOLING

Unless there is a need, it makes no sense to choose a less efficient scheme. How could one justify the 11% power penalty for using supercritical cooling? A brief review of the RHIC layout suggests the following features can only be provided with Supercritical Cooling:

1) The RHIC magnet is designed for optimal performance with a flow of cooling helium through the coil passage,
2) The RHIC magnet does not need ullage space for vapor,
3) There is no need to control liquid level in the magnet,
4) The vacuum jacketed lines and superconducting buses in the ring can be implemented without worrying about elevation change,
5) The warm to cold transition does not need to accommodate flow directions due to elevation changes,
6) It is very simple to provide lead cooling for the CQS magnet (corrector-quadrupole-sextuple),
7) The number of JT valves and level gauges is greatly reduced,
8) Impact on the magnet is minimum after a quench - easy quench handling.

The hypothetical Pool Boiling scheme would place severe limitations on the RHIC layout and operation.

CONCLUSION

With the advantages of Supercritical Cooling for RHIC, it is easy to justify the 11% power penalty needed for Supercritical Cooling with a cold circulating compressor. If an application does not posses similar features, then a comprehensive study must be performed to determine the best cooling scheme.