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COOLING INTRINSICALLY STABLE SUPERCONDUCTING MAGNETS WITH SUPERCRITICAL HELIUM*

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Summary

A number of papers have been written suggesting that superconducting magnets could be cooled by using supercritical helium (helium at pressures above the critical pressure of 2.2 atm). Nearly all schemes for using supercritical helium involve circulating helium inside fully stabilized hollow superconductors. This paper describes a supercritical helium-cooled magnet which is quite different. This magnet, built at LRL, utilizes an intrinsically stable, low-ac-loss superconductor. The heat generated with the coil is conducted to supercritical helium cooling tubes which are adjacent to the magnet coil. (Several superconducting synchrotron groups have suggested this method for cooling pulsed magnets.) This paper describes the experimental equipment, which differs considerably from the normal superconducting magnet system. The problems associated with cooling the magnet are discussed, and the operating characteristics of the coil are presented. In conclusion, the paper presents some of the advantages and limitations involved with this type of magnet cooling.

Introduction

For the sake of this study, supercritical helium is defined as helium gas at pressures exceeding the critical pressure of helium (2.2 atm). Supercritical helium can only exist in one phase, although large variations in density and specific heat are possible at pressures which are just above the critical pressure and at temperatures just above the critical temperature 5.12°K. Supercritical helium, however, is a well-behaved fluid when its pressure is above 8 to 10 atm.¹

Kolm² was one of the first to suggest using supercritical helium as a heat transfer medium for superconducting magnets. Some of the first experimental work on supercritical helium was done in late 1964.² The advent of fully stabilized superconductors made supercritical-helium cooling even more attractive. Brechna^{3,4} did some of the early fully stabilized hollow-conductor experimental studies in 1966 and 1967. The first superconducting magnet to run on supercritical helium was built by Morpurgo⁵ at CERN. This magnet was fully stabilized and used supercritical helium circulated in a hollow superconductor.

A number of authors^{6,7} have suggested that intrinsically stable superconducting dipoles and quadrupoles could be cooled by using supercritical helium. Although the idea of cooling intrinsically stable magnets has been around for some time, to my knowledge no experimental work has been done in this area. The LRL experiment is quite crude, but is unique in a number of ways: (1) The magnet is cooled directly from a 4.5°K refrigerator, thus there is no separate pumping system as in the Morpurgo experiment.⁵ (2) There is no cryostat in the normal sense of the word--the magnet, the cooling coil, J-T valve, and other cooling apparatus are wrapped with superinsulation and put in an insulating vacuum directly. (3) The removal of heat from the superconductor to the supercritical cooling coil is entirely by conduction through a copper paraffin wax matrix. It should be noted that the experiment was also operated in a mode in which the magnet and cooling apparatus were put into a cryostat. A separate cold gas source was used to cool the magnet leads. The results were that there was no lead refrigeration load on the system and there was a quick cooldown from room

temperature to the operating temperature.

Magnet

The magnet is a solenoid with a bore 2.0 in. in diameter and 3.2 in. long, with an overall diameter of 5.0 in. The magnet consists of 4613 turns of 0.020-in. niobium-titanium superconductor with a Formvar insulation. The conductor, which has a copper-to-superconductor ratio of 2.0, has 355 strands of Nb-Ti which are each 0.00061 in. (15.6 μ m) in diameter. The magnet, which was previously well ventilated in boiling helium, was used to measure ac losses in the superconductor. The magnet was capable of being pulsed at 0.4 Hz up to currents of 62 A, which is equivalent to a field in the bore of over 40 kG.

Cooling Apparatus

The magnet cooling coil consists of a length of Mylar-insulated copper tube. This tubing, which is wrapped around the magnet coil, carries the supercritical helium. The magnet, the cooling coil, two thermocouple junctions, carbon resistor temperature-measuring points, and a 40-W heater were all vacuum impregnated and cast in paraffin wax. At each end of the cooling coil is a nickel ceramic joint to prevent the cooling coil from becoming part of a transformer.

One end of the cooling coil, which carries high-pressure gas, is connected to a device which separates the high- and low-pressure streams from the LRL refrigerator remote delivery tube. The other end of the coil goes to an in-line Joule-Thompson (J-T valve). After the gas is expanded in the J-T valve it returns to the refrigerator via the low-pressure side of the refrigerator remote delivery tube. In one mode of operation, a portion of this low-pressure stream, which carries a two-phase mixture of liquid and gas, is bled off to supply gas cooling for the electrical leads (Figs. 1 and 2). In the second mode the lead cooling gas is supplied by a liquid pool below the magnet.

There are pressure taps on both ends of the cooling coil and on the low-pressure side of the J-T valve. Temperatures are measured in the bore of the magnet and on the downstream end of the magnet cooling coil. The magnet windings themselves are cooled by conduction through the copper and wax. In the first mode of operation the magnet, the cooling coil, and the refrigeration apparatus are wrapped with superinsulation and are in a vacuum. During the second mode of operation the magnet and cooling apparatus were in a cryostat, with separate cooling being provided for the gas-cooled electrical leads.

Experimental Results

We first cooled down the magnet directly with supercritical helium by using the electrical leads as a service valve. This was the mode in which cooling for the leads was supplied by the supercritical refrigeration circuit. The magnet took about 3 hours to cool from 295 to 30°K; however, it took 10 hours longer to cool the magnet to between 10 and 15°K (as measured by a carbon resistor). We were unable to cool the magnet from 15 to 5°K by using the J-T loop. The second J-T valve has limited flow capacity at 15°K; as a result, the refrigerator could not supply enough gas to the leads and, at the same time, provide enough return gas

to the lower heat exchanger. A larger second J-T valve would have permitted us to cool the experiment to 5°K and operate the magnet.

The experiment did work in the second mode because the thermal current down the leads was taken care of by a separate source of cold gas. We also had the advantage of cooling the experiment quickly. The source of the cold gas used to cool the leads was a pool of boiling liquid at the bottom of the cryostat below the magnet. This liquid had little effect on the performance of the magnet, which we found from the following: (1) the magnet did not remain superconducting when there was no supercritical helium flowing through the cooling coil, and (2) magnet transitions had no effect on the pool of boiling liquid below the magnet.

We made the following observations while we operated the magnet on supercritical helium. (1) The transition current was reduced from 62 to 53 A (the field generated by the magnet at 53 A is about 35 kG). The reason for the reduced transition current in the higher operating temperature of the supercritical cooled system (5.0 to 5.5°K instead of 4.2°K). (2) Little or no charge rate sensitivity was observed in the magnet. We measured the same transition current over a range of charge rates from 0.06 to 4.8 kG/sec; however, we did not continuously pulse the magnet. (3) When the magnet transitioned at 35 kG it took about a minute for the supercritical cooling to restore the magnet to the superconducting state. (4) The magnet performance was very poor when we shut off either the first or the second J-T valve. (5) Magnet performance got worse when the gas flow in the leads was shut off. More detailed information on the experimental results may be found in Ref. 8.

Concluding Remarks

Our experiment showed that one can cool an intrinsically stable superconducting magnet with supercritical helium, but the procedure for cooling the magnet is not as simple as one might think at first glance. We had a number of vacuum and seal problems before we could get the experiment to run at all. We found, however, that once the magnet was cold and superconducting, supercritical cooling was very satisfactory.

We found that one should expect reduced performance of the superconductor unless special steps are taken to reduce the operating temperature of the magnet. These steps, in my opinion, will increase the cost of the magnet refrigeration system. We found no charge rate sensitivity in our tests, but one should expect the transition current of the magnet to be further reduced by pulsing of the magnet, because the heat transfer from the magnet winding to the cooling coil is rather poor. A substantial improvement in the coil heat transfer may well be required in order to effectively use supercritical helium cooling in a superconducting synchrotron.

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* Work done under the auspices of the U. S. Atomic Energy Commission.

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Fig. 1. Supercritical helium cooled magnet
before casting in paraffin wax.

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Fig. 2. Schematic diagram of supercritical helium cooling circuit. (Note that in second mode of operation the gas-cooled leads receive gas from a separate source and the vacuum boundary is replaced by a cryostat boundary.)

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