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Cooling Large HTS Magnet Coils using a Gas Free-convection Cooling Loop Connected to Coolers

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Abstract. The cool-down and liquefaction of helium in free convection cooling loops has been demonstrated in superconducting magnets greater than 2 meters in diameter. At 4.4K, temperature drops between the magnet hot spot and the coolers of less than 0.2 K have been achieved in large coils that are more than 1 meter from the coolers. At temperatures greater than 20 K, larger temperature drops between the magnet and the coolers are permitted. This paper shows that free-convection gas cooling can be viable for both cooling and cooling down large HTS magnets. This paper presents the flow circuit parameters needed to achieve a reasonable cool-down time and a low temperature drop between the magnet and the cooler cold heads with no liquid cryogen in the loop.

1. Introduction

Gifford McMahon (GM) coolers were invented in 1959 [1]. Two stage GM coolers were described by W E Gifford in 1966 [2]. Two stage cooler that could go to 4 K using a separate J-T loop came along in the late 1960's [3]. Reliable two-stage GM coolers that could go down to 4 K without a separate J-T circuit would became commercially available in the 1990's. The elimination of the separate J-T loop for 4 K cooling was made possible by high heat capacity regenerator materials [4]. This made the cooling of low temperature superconducting magnets cooled with cooler a viable proposition. GM pulse tube coolers were described by W E Gifford and R C Longworth in 1964 [5]. Two stage 4.2 K GM coolers and GM pulse tube coolers became available in the 1990's because of the improved regenerator materials. Helium liquefaction from warm gas using two stage pulse tube coolers was demonstrated in the late 1990's [6]. In 2008, in connection with the MICE Experiment in the UK, it was shown liquefaction of hydrogen or helium could be done using any kind of two stage cooler provided the gas being liquefied is properly pre-cooled by liquid nitrogen and the cooler stages before condensation [7].

When coolers became reliable enough to become a commercial product, the cold heads were attached directly to the load being cooled. In 1970's Maser amplifiers in microwave antennas were cooled using GM coolers. GM coolers were selected because they could move with the antenna and their cooling performance was independent of the cooler orientation. Thousands of GM coolers were sold by CTi, an American company near Boston, for this purpose and the cooling masers, cryogenic detectors, and for cryogenic vacuum pumps. The coolers required regular maintenance, which was deemed acceptable as long as there were back-up systems available. During the 1970's and 1980's

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coolers were used as re-condensers on superconducting magnet systems magnets that were in remote locations where there was no access to liquid helium and the magnet was operated in persistent mode. In the 1990's the MRI industry started using coolers for re-condensing helium in their magnets, which operated in persistent mode. The commercial availability of HTS power leads where the warm end was cooled either by liquid nitrogen or the cooler first stage made it possible to continuously power a magnet from an external power supply. This eliminated the need for lead retraction and it allowed the field to be changed on demand. The Superbend Dipole magnets used on the Advanced Light Source at Berkeley [8] were cooled with two-stage GM cooler second stages that were attached directly to the dipole magnet with LTS superconducting coils. Once the dipole magnet was cooled-down, liquid helium was put into tank attached to the dipole magnet iron. The liquid helium acted as reserve cooling for the magnet. The magnet shield was cooled initially with liquid nitrogen in a tank before the coolers were turned on. When the magnet and the shield were at their final operating temperature, the nitrogen in the tank was frozen at a temperature of ~50 K. The frozen nitrogen in the tank acted as reserve cooling for the shield and the HTS leads. The Superbend magnets at Berkeley have operated for over 16 years, with only periodic maintenance of the coolers and their compressors.

2. Free Convection Cooling Loops with Liquid-helium and Gas in Pipes

In 2002 the Lawrence Berkeley Laboratory was building and ECR ion source for the Berkeley 88-inch cyclotron. This superconducting magnet was to be kept cold with four GM coolers capable of delivering 6 W of cooling at 4.7 K. When this magnet was first tested, the cooler cold head was in liquid helium. The liquid level in the cryostat was rising as the pressure was rising. Liquid helium expands about 20 percent per degree as it gets warmer. Eventually the cryostat relief valve vented because the cold head was immersed in liquid helium and the heat transfer to the liquid helium was poor. From this revelation, the natural convection liquid-helium and helium-gas natural convection cooling loop was born. This concept isn't any different than condensing helium gas back into liquid in an open cryostat except the liquid phase is delivered to the bottom of the cryostat through a pipe while the gas phase flow to the condenser through another pipe. The beauty of this concept is that the temperature of the liquid in the cryostat can be only 0.1 K warmer than the condenser attached to the cooler cold head and this temperature difference is almost independent of the distance between the cold head and the liquid helium surface in the cryostat [9]. In 2003, this author used the same concept and applied it to liquid-gas cooling loops containing helium, hydrogen, and neon [10].

In 2004, the MICE experiment decided to cool the channel superconducting magnets with coolers in order to avoid having to buy a central refrigerator. This was a mistake for many reasons, but it did lead to some experiments that showed that one could potentially cool-down channel magnets and fill them with liquid helium generated from 300 K helium gas [11], [7]. In 2012, this author advocated building an ECR ion source magnet cooled with a liquid-gas cooling loop that connected several coolers to the magnet in a cryostat with minimum liquid helium volume [12].

The cyclotron gas-stopper magnet at Michigan State University is a sector cyclotron with 2-meter diameter iron poles. The magnet iron and the two coil cryostats were designed to be split to allow access to the system that decreases the energy of the heavy ions entering the cyclotron. The magnetic induction in the 180 mm gap between the poles is about 2 T with 700 kA turns in the two coils. The magnet was originally designed to be cooled-down and cooled using a large helium refrigerator located 200 m from the magnet. In 2013, the magnet cooling system was changed from a central-refrigeration based system to a cooling system based on using six Cryomech PT415 pulse tube coolers for cooling the two Nb-Ti coils in separate cryostats [13]. The cooling system for this MSU magnet was designed so that the magnet could be cooled-down using the coolers. The 24 liters of liquid helium in the two cryostats was to be liquefied from warm helium gas. The flow channels around the coils were suitable for forced two-phase helium cooling or free-convection two-phase cooling with a column of liquid helium as the driving force. Since the coils and the cryostat had been fabricated, the magnet flow system was not optimized for free-convection cool-down [14], [15]. Figure 1 shows the MSU cyclotron gas-stopper magnet. Figure 2 is a coil cooling circuit schematic with three coolers.

Fig. 1. MSU cyclotron gas-stopper Magnet as seen from the end.

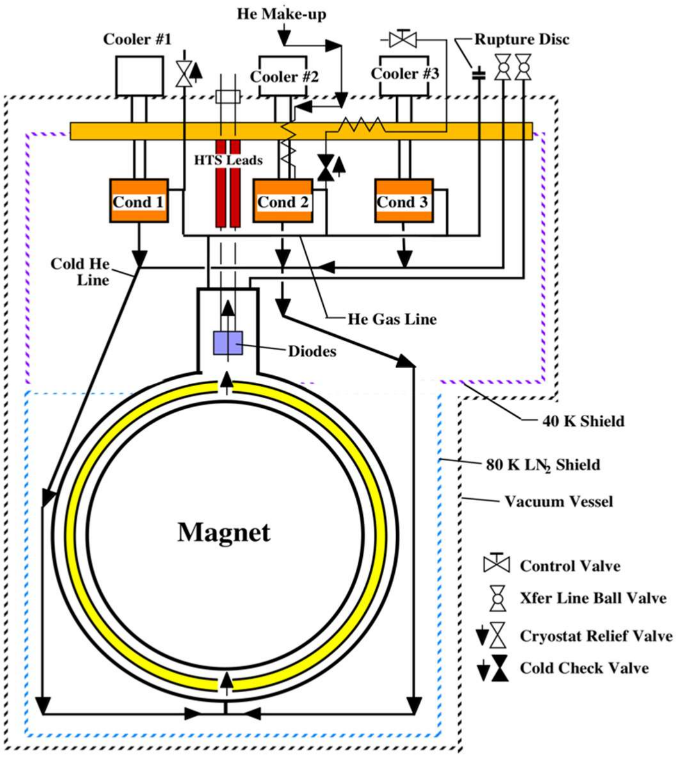

Fig. 2. A Schematic of the cooling system for each coil of the MSU cyclotron gas-stopper magnet.

Figure 2 above shows the three pulse tube coolers connected to each coil of the MSU gas-stopper magnet. Figure 2 is not drawn to scale; the magnet cryostat is much larger than the three cooler assembly. The three coolers and their heat exchangers must be above the magnet assembly and the magnet cryostat neck. We found out that the magnet and cryostat assembly cool-down took about three times longer than our original cool-down calculations. This means that the average mass flow through the flow loop was about a factor of three too low. The reasons for this were: 1) The size of the flow channels in the magnet cryostat were much smaller than the drawings indicated. 2) There was almost no flow in the channels on the outer radial surface of the coil. 3) There were a large number of momentum jumps within the magnet cryostat. 4) The flow circuit resistance through one cooler heat exchanger was much larger than for the other two cooler heat exchangers. 5) The cryostat pressure during the cool-down was limited by the pressure rating of the bellows in the system. Increasing the cryostat pressure allows the coolers cold heads to operate at a higher temperature, which decreases the cool-down time. 6) Increasing the U factor and the area of the heat exchanger attached to the cooler cold head would increase the heat transfer to the cold heads.

We changed the place where the helium gas entered the system during liquefaction. When helium gas was injected to the manifold to all three cooler heat exchangers, the time to fill the cryostat with liquid helium increased by a factor of three. Once the magnet cryostat was filled with liquid all three cooler cold heads appeared to be at nearly the same temperature, which was below 4.2 K. When we turned off one cooler, the cold head temperature of the other coolers rose to about 4.6 K. The first stage temperature of the remaining coolers rose to about 40 K. The temperature drop from the magnet coils in liquid helium and the cooler cold heads was about 0.1 K. The cooler cold head heat exchanger area of about 0.05 square meters is more than adequate for re-condensation of the helium.

3. Helium and Hydrogen Gas Cooling Loops for Cooling HTS Magnets

Liquid hydrogen would be an ideal coolant for HTS and magnesium di-boride magnets between 15 K and 28 K were it not for its flammability and related safety issues [16]. Hydrogen has a large heat of vaporization (~442 J per g at 20.7 K) [17], thus the mass flows in a two-phase circuit are twenty times lower than for helium at 4.2 K. The temperature drop between the liquid and the cooler cold head heat exchanger is about 0.2 K [10], [18] with eight times the heat flow. Liquid neon is a poor substitute for hydrogen because of its rarity, low thermal conductivity and low specific heat [18].

In 2016, this author compared the cool-down time for a mass of 1250 kg using a thermal-siphon convection cooling loop using a single Cryomech PT415 two stage cooler [19]. The cold mass was cooled through four tubes that are 12.7 mm ID and 3.8 meters long. The total surface area of these tubes was ~0.62 square meters. The area of the cooler second stage heat exchanger (condenser) used in the study was ~0.18 square meters. Figure 3 shows the calculated cooldown time from 300 K to the 1 atmosphere boiling temperature of helium, hydrogen and neon when these three gases are in the cooling loop. The calculations were done at loop pressure of 0.2 MPa and 8 MPa down to 60 K. Increasing the pressure in the cooling loop from 0.2 MPa to 8 MPa reduces the cool-down time by ~1.65 for helium and hydrogen and by ~1.85 for neon. The cool-down time ratio for hydrogen to helium is ~ 0.9, whereas the cool-down time ratio neon to helium is ~1.7. Neon is clearly not a substitute for hydrogen or helium, but helium can be substituted for hydrogen with a small penalty. The thermal conductivity and viscosity of the two gases are similar at temperatures from 15 to 40 K

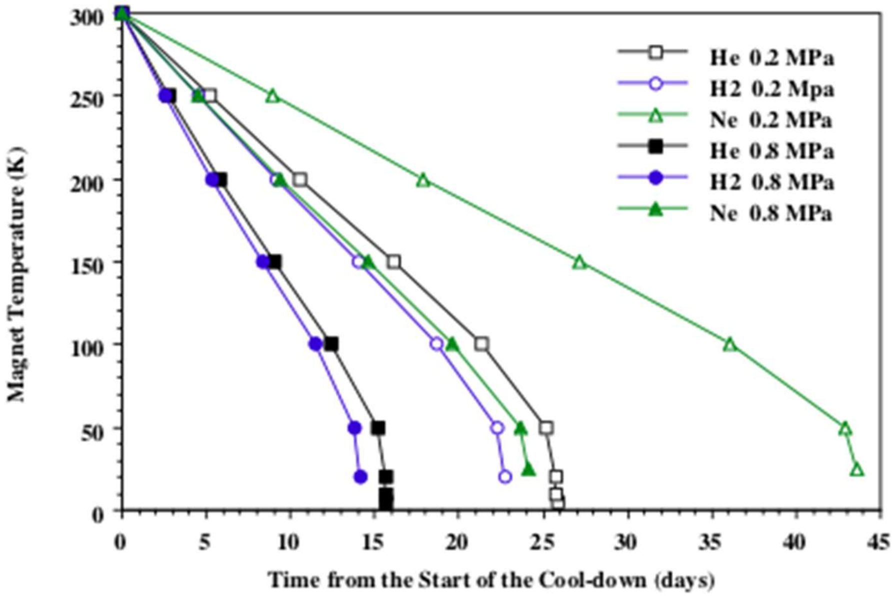

Figure 3. 1250 kg cool-down time from 300 K with helium hydrogen and neon with PT415 cooler.

For an HTS magnet [20] one might want to use a Cryomech AL-325 single stage GM cooler [21] in place of a single PT415 two stage cooler. In this case, the shield and the tops of the HTS leads would be liquid nitrogen cooled. The AL-325 cooler produces 40 W of cooling at 15 K, 70 W at 20 K and 140 W at 30 K. The cooler efficiency at 30 K is about 12 percent of Carnot. The magnet cool-down time for 1250 kg with this cooler would be reduced by over a factor of two, but the product of the heat exchanger U factor times area must be increased by a factor of five compared with the PT415 cooler heat exchanger. A magnet at 30 K could be provided with 50 W of extra cooling using this cooler.

Gas cooling loops are possible with hydrogen or helium. The temperature drop between the hottest part of the magnet and the cold head is always larger than for a two-phase loop. This may be acceptable for an HTS magnet that is operating at about 30 K. As the heat in the system increases the cold head temperature and the system ΔT increase proportionally to the heat load. In an HTS magnet, this can be unstable because as the magnet hot spot temperature goes up more heat is produced.

Liquid hydrogen is the best coolant in the temperature range from 15 to 28 K, but the safety system must be completely passive with all of the hydrogen in the system stored in an external buffer tank. The total amount of liquid hydrogen in the magnet system must be less than 5 liters.

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