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A case study of MgB_2 and HTS magnets being cooled and cooled down using a hydrogen thermal-siphon cooling-loop with coolers

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Abstract

When one fabricates a magnet using MgB_2 or HTS conductors, the operating temperature of the magnet can be increased into the temperature range from about 15 to 30 K. This temperature range is between the triple-point (13.8 K) and the critical point of para-hydrogen (32.3 K). Hydrogen has excellent heat transfer properties both as a liquid and as a gas at low temperature. The heat of vaporization of hydrogen is larger than any cryogenic fluid. In addition, the specific heat of the liquid and the gas is higher than any cryogenic fluid. Hydrogen may be the best fluid to use to connect a magnet operating between 15 and 30 K with a source of refrigeration. This paper compares magnet cooling at 20 K using helium and hydrogen. A safe completely passive cooling loop is discussed in this paper.

Keywords: Hydrogen; Helium; MgB_2; Magnet; HTS Magnet; Thermal-siphon Cooling Loop

1. Introduction

Thermal-siphon cooling loops have been used to cool superconducting detector magnets since the 1970's [1]. This involved using natural convection and the phase separation of helium gas from liquid helium to drive the cooling loop. A refrigerator produced the liquid helium and took back the cold gas. MRI magnets and other types of magnets have been kept cold using re-condensers connected to the cooler cold head [2]. Thermal-siphons have been used in conjunction with condensers to ensure that cold liquid helium enters the system at the bottom, which

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maximizes the efficiency of the cooling process [3]. With such systems the cool-down a cryostat and liquefaction of helium into that cryostat was demonstrated using small coolers [4].

The cyclotron gas stopper magnet at Michigan State University (MSU) uses six pulse tube coolers (three for each coil) that generate 1.35 W at 4.2 K on each cooler second-stage while producing 36 W of cooling on each first stage to cool-down and keep cold a 2500 kg of total cold mass [5] [6]. This magnet was tested in 2014 and 2015 [7]. This paper discusses whether this technique can be used to cool-down, liquefy, and keep the magnet cold using hydrogen as a working fluid instead of helium. A number of people have proposed hydrogen cooling HTS magnets [8], [9]. A passive liquid hydrogen thermal siphon cooling loop, using a two stage cooler 4 K was discussed by Green [10] in 2013. This paper compares a hydrogen-cooled magnet with a helium-magnet of the same size and mass as the MSU cyclotron gas-stopper magnet, which took ~14 days to cool-down with helium at 2 MPa.

2. Why use liquid hydrogen cooling HTS and MgB_2 magnets?

Para-hydrogen is in the liquid state from 13.81 K (triple point temperature) to 32.3 K (the critical temperature) is potentially attractive for cooling MgB_2 and HTS magnets. If two-phase hydrogen is used in a passive cooling loop cooled by a cooler, the magnet temperature can be kept at a constant temperature that is within 0.2 to 0.3 K of the cooler cold head temperature. Liquid hydrogen has the highest heat of vaporization of any cryogenic fluid. The C_p of hydrogen is the largest for any gas or liquid. Table 1 compares the properties of helium and hydrogen. Hydrogen is a potential fluid for use in a thermal-siphon cooling loop for cooling down, liquefying and keeping a magnet cold.

Table 1 Helium and Hydrogen Parameters [11]

Parameter	Fluid	
	He	H_2
Triple Point T (K)	2.17	13.81
Triple Point P (kPa)	5.1	7.0
Boiling T T_b at 101.3 kPa (K)	4.22	20.4
Liquid Density at T_b (kg m^{-3})	125	70.8
Critical T (K)	5.19	32.3
Critical P (kPa)	221	1292
Heat of Vaporization (J g^{-1})	20.9	442
C_p Liquid at T_b (J g^{-1} K^{-1})	~2.5	~9.8
C_p Gas at T > 2T_b (J g^{-1} K^{-1})	~5.2	~14.2
k_f Liquid at T_b (W m^{-1} K^{-1})	0.027	0.119
k_f Gas at T_b (W m^{-1} K^{-1})	0.011	0.021
μ liquid at T_b (kg m^{-1} s^{-1})	3.5x10^{-6}	1.3x10^{-5}
μ gas at T_b (kg m^{-1} s^{-1})	0.9x10^{-6}	1.1x10^{-6}
Max Nucleate Boiling Q (W m^{-2}) [12]	~8000	~90000
Film Boiling h_c (W m^{-2} K^{-1}) [12]	~670	~330

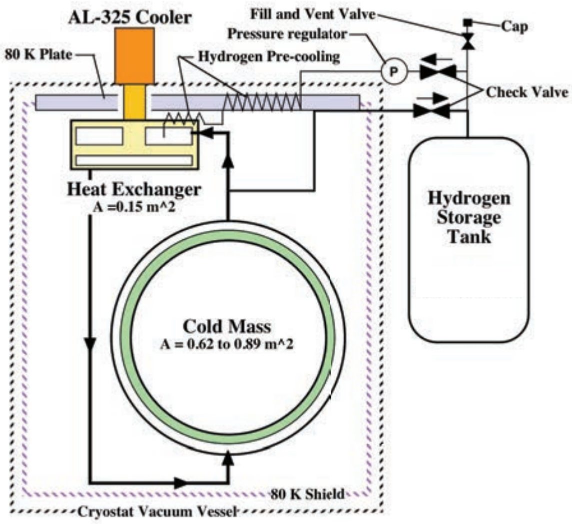

Figure 1. A schematic diagram of a hydrogen Thermal-siphon cooling-loop for a magnet

3. A passive two-phase hydrogen cooling loop with a single-stage cooler

Figure 1 above shows a simplified version of a passive liquid hydrogen cooling-loop. The cooling-loop is filled with hydrogen gas and capped before the cold mass is cooled down. The size of the hydrogen storage tank is a function of the amount of liquid hydrogen that is produced by the cooler [10]. For 3.0 L of LH_2 at 20 K, the tank size is ~250 L at a pressure 1 MPa. The use of a passive cooling loop avoids most of the flammable gas safety hazards associated with hydrogen [13], [14]. The cooler shown in Figure 1 is a Cryomech AL-325 single-stage GM cooler [15]. This cooler produces 0 W at 11 K, ~70 W at 20 K, ~140 W at 30 K ~230 W at 50 K and 290 W at 90 K.