Helium-Liquefaction by Cryocooler for High-Field Magnet Cooling

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ABSTRACT

Helium liquefaction by a two-stage pulse-tube cryocooler is presented. This study is motivated mainly by our recent development of a closed-loop cooling system for 21T Fourier transform ion cyclotron resonance mass spectrometer (FT-ICR MS) superconducting magnets without any replenishment of the cryogen. Since the cold surface of a cryocooler is very limited, a cylindrical copper fin was thermally anchored to the first and second stage coldheads in order to extend the available heat transfer surface. A heat exchanger tube was attached on the outer surface of each cylindrical fin, and heat exchange occurs between the tube and the helium gas that is passing through the tube. The refrigeration capacity of the two-stage pulse-tube cryocooler has been measured, and, taking into account the refrigeration capacity of the cryocooler, the temperature distribution along the copper cylinder and heat exchanger tube has been calculated using a relevant heat transfer analysis. The effect of the cryocooler refrigeration capacity on the liquefaction has also been investigated.

INTRODUCTION

Over the past several years cryocoolers have been applied to many science applications such as space exploration, cryogen storage, and medical instruments. One of the large markets for cryocoolers, because of their reliability and efficiency, is high field magnet instruments like NMR (Nuclear Magnetic Resonance), FT-ICR or MRI (Magnetic Resonance Imaging). An international collaboration between KBSI (Korea Basic Science Institute) and NHMFL (National High Magnetic Field Laboratory) is underway to develop a 21 T FT-ICR MS. The objective of the project is the design of compact and efficient magnet systems operating at 1.8 K. As a first step, we have proposed the closed-loop cooling system shown in Fig. 1 for cooling 21 T FT-ICR magnets.[1] The low temperature superconducting magnets are immersed in a subcooled helium bath that is connected to the 4.2 K reservoir through a narrow channel. Saturated liquid helium is cooled via a Joule-Thomson (JT) heat exchanger and flows through a JT valve, isenthalpically dropping its pressure to approximately 1.6 kPa, corresponding to a saturation temperature of
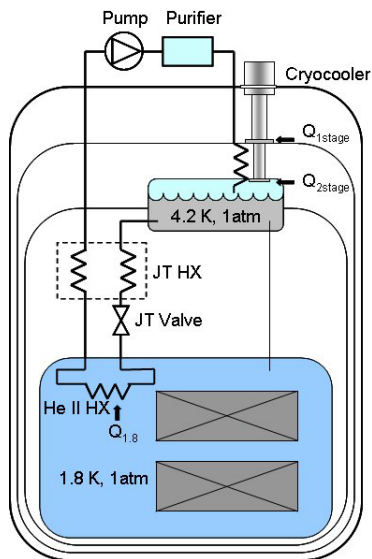
Figure 1. Schematic of closed-loop cryogenic system for 21 T FT-ICR magnets.

1.8 K as it enters the helium II heat exchanger. Helium leaves the He II heat exchanger as vapor, passing through the JT heat exchanger. The helium vapor leaves the cryostat and goes into a vacuum pump located outside of cryostat. Now, helium is then purified and liquefied by a two-stage cryocooler and is stored in a 4.2 K reservoir maintained at a certain liquid level.

The closed-loop cooling system has great advantages with respect to efficiency and compactness, since no replenishment of cryogen is necessary after cool-down. However, the heat transfer analysis to accurately predict the temperature distribution of the heat exchanger attached to the coldhead for helium liquefaction is crucial in order to confirm the feasibility of our presented design. In this paper, we present an approach for helium liquefaction using a two-stage cryocooler, with an emphasis on the detailed design of the cryocooler heat exchanger. A refrigeration performance test of the two-stage pulse-tube cryocooler that will be employed in the cryogenic system was performed in order to obtain the refrigeration capacity of the cryocooler over a wide temperature range. The dimensions of the heat exchanger for helium liquefaction at the first and second stage coldheads were also determined from the relevant heat transfer analysis.

CRYOCOOLER PERFORMANCE MEASUREMENT

The test set-up for cryocooler performance measurement consisted of a cryocooler, heaters and temperature sensors. A two-stage pulse-tube cryocooler (Cryomech Model PT415) was mounted directly to the top plate of the cryostat, and a heater was positioned at the top of each coldhead, which was made of oxygen free high conductivity copper. A cylindrically-shaped cartridge heater was inserted into a copper clamp that was attached to the coldhead with screw and washer, and cryogenic thermal grease was applied between the coldhead and copper clamp as a thermal contact medium, ensuring maximum thermal conductance. The heating power at each stage was regulated with an individual DC power supply. A calibrated platinum resistance thermometer (Lakeshore PT103) and Cernox[TM] were attached to the top of the first-stage and second-stage coldheads, respectively. A solid thermal shield was attached to the first-stage coldhead, and the entire cold part of the cryocooler was wrapped with multilayer insulations (MLI) to minimize the thermal radiation load.
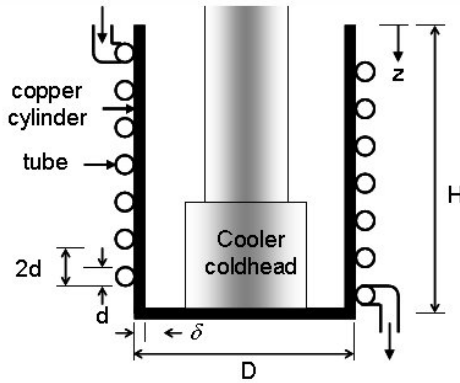
Figure 2. Cryocooler heat exchanger on extended surface of copper cylinder.

At the initial phase of the experiment, the cryostat was pumped down to the range of 5×10^{-5} torr and then cooled down to near liquid helium temperature. Once each cryocooler coldhead was cooled down, a uniform heat flux was supplied to the heater. Temperatures and heating powers were recorded every 12 seconds with a data acquisition system operated through LabView[TM] software. Variable in this experiment was the amount of heating power supplied to each coldhead of the cryocooler.

CRYOCOOLER HEAT EXCHANGER

The purified helium gas is cooled down by the first-stage coldhead and then liquefied by the second-stage coldhead of the cryocooler. Since the coldhead of the pulse-tube cryocooler has a very limited surface area, a cylindrical copper fin was thermally anchored to the coldhead, and a heat exchanger tube was attached on the outer surface of the cylindrical fin as shown in Fig. 2. The helium temperatures at the inlet of the first and second heat exchangers can be assumed to be room temperature and the temperature of the first-stage coldhead, respectively. Heat flow in this system includes conduction through the copper cylinder and forced convection between the helium gas and the heat exchanger tube. The problem is formulated in order to determine how the size of the copper cylinder and tube and mass flow rate affect the exit temperature of the heat exchanger tube. The axial temperature distribution of the copper cylinder and the helium temperature in the tube can be determined from the energy balance equations.

$$\pi D \delta \cdot k(T_C)\frac{d^2 T_C}{dz^2} + h\frac{\pi^2 D}{2}(T_{He} - T_C) = 0 \tag{1}$$

$$\dot{m}_{He} C(T_{He})\frac{dT_{He}}{dz} - h\frac{\pi^2 D}{2}(T_{He} - T_C) = 0 \tag{2}$$

In Eq. (1) and Eq. (2), the subscripts of C and He denote copper and helium, respectively. The thermal conductivity of copper, k, and specific heat of helium gas, C, are temperature dependent and determined from CRYOCOMP®.[2] The heat transfer coefficient for forced convection in a round tube can be evaluated as a function of Reynolds number,

$$Re = \frac{4\dot{m}_{He}}{\mu \pi d} \tag{3}$$

The heat transfer coefficient, h, is calculated by introducing the Nusselt number (Nu) and is determined as follows [3,4]

$$Nu = \frac{h\,d}{k} = 4.36 \quad for \quad Re < 3000 \tag{4}$$

$$Nu = \frac{h\,d}{k} = 0.023\,Re^{0.8}\,Pr^{0.3} \quad for \quad Re \geq 10^4 \tag{5}$$

Boundary conditions for the first-stage heat exchanger are as follows

$$T_{He} = 300K, \ \frac{dT_C}{dz} = 0 \quad at \quad z = 0 \tag{6}$$

$$T_C = T_{Cooler,1st} \quad at \quad z = H \tag{7}$$

and for the second-stage heat exchanger are as follows

$$T_{He} = T_{Cooler,1st}, \ \frac{dT_C}{dz} = 0 \quad at \quad z = 0 \tag{8}$$

$$T_C = T_{Cooler,2nd} \quad at \quad z = H \tag{9}$$

The energy balance equations can be solved simultaneously by numerical methods. A fourth-order Runge-Kutta method was employed for numerical integration, and the shooting method of linear interpolation was used for improving the initial assumption.[5]

RESULTS AND DISCUSSION

Figure 3 shows the temperature history of the first and second stage coldhead after turning on the cryocooler. During the initial cool-down the temperatures decreased almost at a constant rate; it took approximately 1 hour for the first-stage coldhead to reach 31 K, and 50 minutes for the second-stage coldhead to reach 4.2 K. Heater power was then supplied to the second-stage coldhead from 0.5 W to 3.0 W in 0.5 W increments, while the heating power to the first-stage coldhead was maintained at 0 W (see inner graph). The temperature at each power level was recorded once the system reached steady state, which took approximately one-half hour.
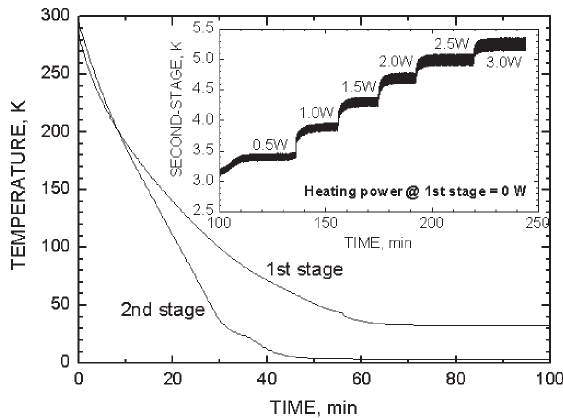

Figure 3. Temperature history of first and second stage coldhead after turning on cryocooler
(Inner graph: Temperature of second-stage coldhead when first-stage heating power is zero)
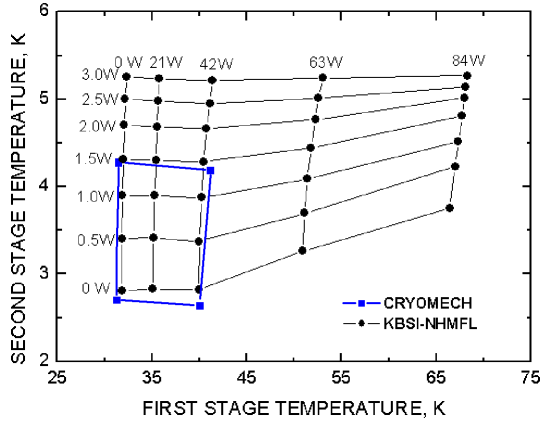
Figure 4. Listed and measured refrigeration capacity of Cryomech PT 415

Shown in Fig. 4 is the measured refrigeration capacity of the PT 415 cryocooler as a function of each stage coldhead temperature, in comparison with the capacity provided by the manufacture.[6] The temperatures of each coldhead are average values of two measurements. Fair agreement is observed, even though there is a slight deviation in actual performance. For a given heating power to the first-stage coldhead, the temperature of the second-stage coldhead rises with increasing heating power to the second-stage coldhead, and the interval between adjacent temperatures decreases upwards. When the heating power to the first-stage is below 42 W, the temperatures of the second-stage coldhead are almost constant even though the heating power to the first-stage coldhead increases. When the heating power to the first-stage exceeds 42 W, the temperatures of the first-stage coldhead increase more rapidly than the case of heating power less than 42 W. The temperatures of the second-stage coldhead are almost constant when heating power to the second-stage coldhead is 3.0 W.

The calculated helium temperature at the exit of the first-stage heat exchanger is plotted in Fig. 5 as a function of the copper cylinder diameter. In the calculation, the mass flow rate of helium is 0.025 g/s, and the height of copper cylinder (H) and the diameter of copper tube (d) are 150 mm and 4.7 mm, respectively. The temperature of the first-stage coldhead is 52 K and that
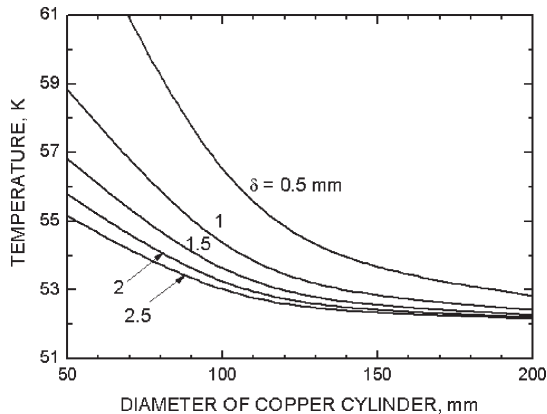

Figure 5. Temperature at exit of first-stage heat exchanger
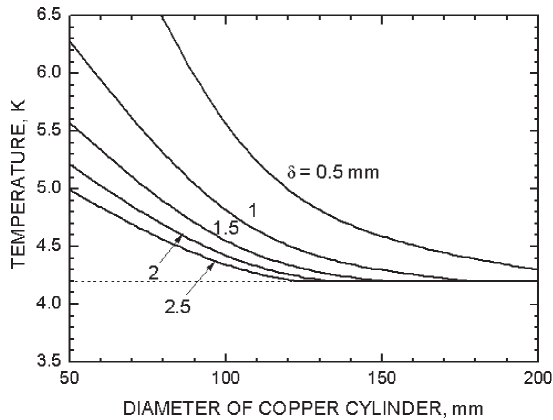
Figure 6. Temperature at exit of second-stage heat exchanger

of the second-stage coldhead is 4.0 K; these are based upon the total heat budget at each stage (65 W for first-stage and 1.0 W for second-stage)[1] and the refrigeration capacity of the present cryocooler as shown in Fig. 4. As the diameter of the copper cylinder increases, the exit temperature of helium decreases and converges to a constant temperature. Also, the exit temperature decreases as the thickness of the copper cylinder increases.

Figure 6 shows the calculated helium temperature at the exit of the second-stage heat exchanger as a function of copper cylinder diameter. The inlet temperature of helium is 52.4 K when the diameter and thickness of copper cylinder for first-stage heat exchanger are 150 mm and 2 mm, respectively. As the diameter of the second-stage copper cylinder increases, the exit temperature of helium decreases and converges to 4.2 K as phase-change occurs. As with the first-stage, the exit temperature decreases as the thickness of copper decreases. A cylinder diameter over 120 mm is required in order to achieve a temperature of 4.2 K at the exit, depending upon the thickness of the cylinder. A diameter and thickness of 150 mm and 2 mm, respectively, should provide a reasonable design for the copper cylinder when the helium enters the heat exchanger at 52.4 K.

CONCLUSIONS

A comprehensive heat transfer analysis has been presented to evaluate helium liquefaction by a cryocooler for high-field magnet applications. The actual refrigeration capacity of a two-stage pulse-tube cryocooler (PT 415) was measured over a wide temperature range from 50 to 70 K. This performance was then used for the design of a closed-loop cooling system for the 21 T FT-ICR magnets. In order to liquefy the helium, detailed dimensions of first and second-stage coldhead heat exchangers were determined using the heat transfer analysis. Experimental verification of the system will be performed in the near future.

ACKNOWLEDGMENT

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