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Second stage cooling from a Cryomech PT415 cooler at second stage temperatures up to 300 K with cooling on the first-stage from 0 to 250 W

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Abstract. The amount of cooling delivered to the second stage of a two stage cooler is dependent on the second stage temperature and the amount of refrigeration provided by the cooler first stage. The second stage cooling as a function of temperature for a Cryomech PT-415 cooler (1.5 W at 4.2 K with 42 W on the first stage) has been estimated by scaling similar data that was measured for a Cryomech PT-410 cooler (1.0 W at 4.2 K with 28 to 30 W on the first stage). In order to accurately calculate the cool-down time for a superconducting magnet using PT-415 K coolers one must know how much cooling can be delivered by the cooler second-stage as a function of the second-stage temperature and the added cooling delivered to the cooler first-stage. There are applications where PT415 coolers are used in the temperature range from 15 to 25 K to liquefy hydrogen or cool magnets fabricated from MgB₂. This report describes the method for estimating the cooler performance for a PT415 cooler as well as the results of the measurements on several PT415 coolers.

1. Introduction

The Cryomech PT410 and PT415 pulse tube coolers are used for cooling superconducting magnets and other applications [1]. These coolers are also the central element in the small helium liquefiers produced by the company for universities and other institutions that require liquid helium for research and product development [2]. Most of the uses for these coolers involve the re-condensation of liquid helium using a thermal-siphon cooling-loop or in a liquid helium tank [3], [4]. When a cooler is used for helium re-condensation, the cooler second stage performance 4.2 K is often all that is needed. When something goes wrong with a magnet cryostat or magnet cooling system, more knowledge about the cooler performance is needed to determine what went wrong [5], [6]. Using a cooler to cool-down a cryostat requires knowledge of the cooler performance over a wide temperature range [7].

Cooler operating data over a range of temperatures on both stages is critical for understanding how a device is cooled-down using these coolers. Two-stage coolers may also be used for cooling at higher temperatures (say up to 28 K) to cool MgB₂ magnets [8]. These coolers can also be used for the hydrogen liquefaction and hydrogen re-condensation after liquefaction [9], [10]. For these reasons, it is important to understand how these coolers behave as a function of 1st and 2nd stage temperatures.



2. Estimating PT415 Performance based on PT410 Performance Measurements

In order to understand how a thermal siphon cooling loop behaves during a magnet cool-down one must have cooler performance curves that apply to the coolers that are being used to cool-down a magnet or other device. This statement is also true for cryogen free systems as well. Michigan State University (MSU) looked at cooling down two systems using a thermal-siphon cooling loop. These systems are; 1) an ECR Ion source magnet [11] and 2) the cyclotron gas-stopper magnet [7], [12]. In both cases, MSU used the measured extended PT410 cooler parameters to estimate the performance of the PT415 cooler and the PT415-RM cooler (the remote valve motor version of the PT415 cooler that is used in certain circumstances where there are high magnetic fields [13] or high voltages [14]). Figures 1 and 2 show the measured performance of the PT410 cooler taken in 2004 [1].

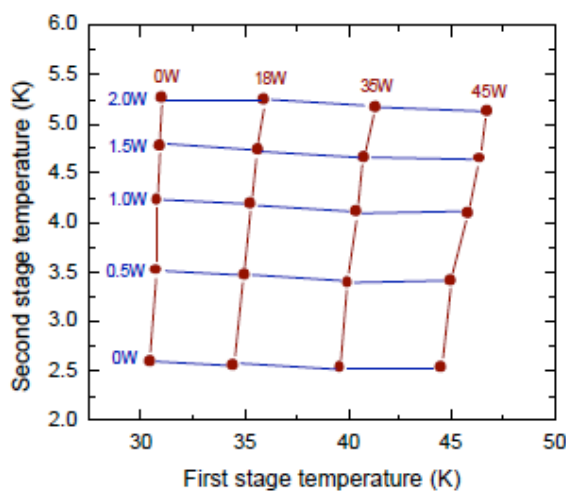


Figure 1. The operating parameters of a PT410 cooler in the nominal liquid helium range on the cooler second-stage.

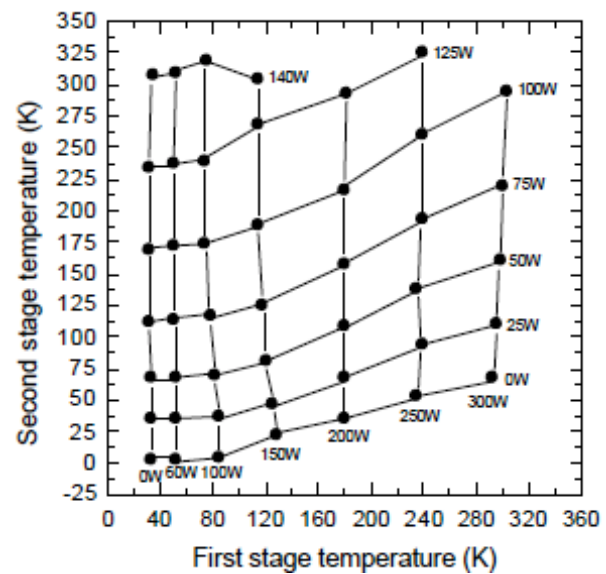


Figure 2. The extended operating parameters for a PT410 cooler from zero to 300 K on both the first and second stages of the cooler.

From the data in Figure 1 and Figure 2, MSU estimated what the output of the PT415-RM coolers might be. The heat loads on the second-stage and first-stage was multiplied by 1.35 because a remote motor PT415 cooler has an output of 1.35 W at 4.2 K and about 36 W at 40 K as compared to 1.5 W at 4.2 K and 40 W at 40 K for a standard PT415. This assumption was used to calculate the refrigeration on the cooler second-stage at temperatures above 4.2 K. This cooling model was used to calculate the cooling needed to cool-down 1240 kg of cold mass in each of the cyclotron gas stopper magnet coils and cryostats plus the mass of the second stage cold heads, the condenser heat exchangers, and the pipes that connect the coolers to the magnet cold mass. The mass cooled-down was supposed to average about 425 kg per cooler.

Figure 3 shows the refrigeration R on the second stage is plotted as a function of the second stage temperature T of a PT415-RM cooler from the model based on the PT410 cooler with no heat on the 1st-stage. From this graph a curve fit was made. The equation developed from the fit is as follows;

$$R = -5.259 + 1.4738T - 8.8986 \times 10^{-3}T^2 + 5.2029 \times 10^{-5}T^3 - 1.3019 \times 10^{-7}T^4. \quad (1)$$

Figure 4 shows the inverse case where the temperature of the 2nd-stage cold head T is plotted as a function of the heat load on the 2nd-stage cold head Q with heat on the 1st-stage. From this graph a curve fit was made. The fitted equation was used in the model of the cool-down of the MSU cyclotron

gas-stopper magnet coils using three PT415-RM coolers to cool-down each of the magnet coils. The equation developed from the fit is as follows;

$$T = 2.415 + 1.1719Q - 2.639 \times 10^{-2} Q^2 + 6.7884 \times 10^{-4} Q^3 - 6.189 \times 10^{-6} Q^4 + 1.953 \times 10^{-8} Q^5. \quad (2)$$

The fit of equations (1) and (2) is pretty good with an $R^2 = 1.000$. The equations don't fit the data very well at very low temperatures or at temperatures above 170 K

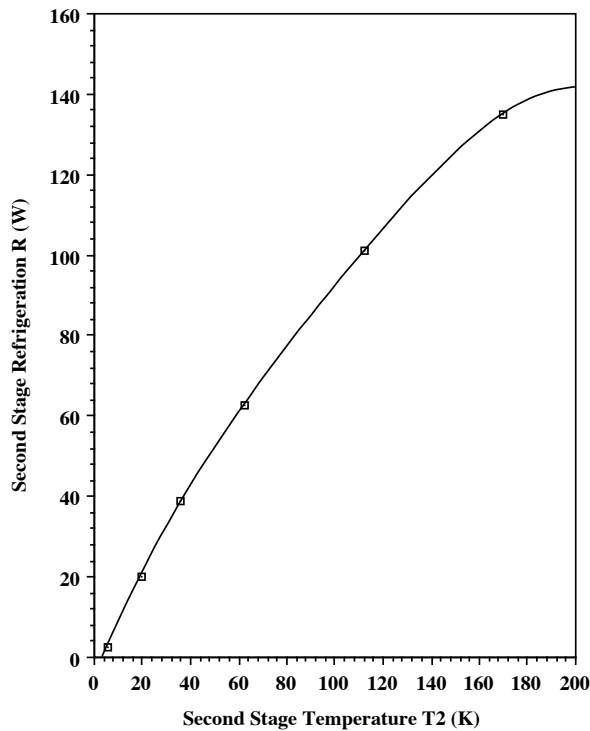


Figure 3. A model of the 2nd stage refrigeration as a function of the 2nd stage temperature for a PT415-RM cooler based on a PT410 cooler.

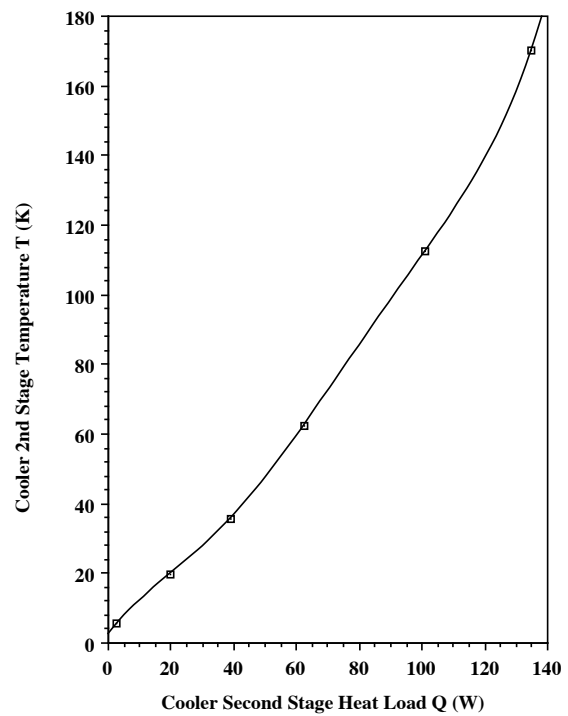


Figure 4. A model of the 2nd stage temperature as a function of the 2nd stage heat load for a PT415-RM cooler based on a PT410 cooler.

The model based on a PT410 cooler worked reasonably well for modeling the performance of a thermal-siphon cooling loop as the cyclotron gas-stopper magnet was built. We know from Cryomech measurements extended performance that this model doesn't work very well at high heat loads on the cooler. The model worked reasonably well for cooler heat loads between 10 W and 60 W. For cooler heat loads above 75 W, the cooler performance deviates substantially from measured performance of a PT415 cooler. The fit falls apart above $R = 120$ W. The performance curves in Figures 3 and 4 don't fit very well at low heat loads as well. These difficulties didn't affect the modeling of the cool-down of the cyclotron gas-stopper magnet cool-down very much [15]. It was clear that more temperature data was needed for second stage heat loads between 3 W and about 80 W.

3. Methodology for measuring Cooler Performance

All of the cooler performance data taken used same methodology. The cooler must be in a good vacuum during the test. The part of the cooler below the first stage of the cooler must be in a shield that is cooled by the cooler first stage. The shield should have a low emissivity surface and there should be at least five layers of MLI between the shield and the second stage cooler parts. There must be at least ten layers of MLI between the shield and the first stage parts and the vacuum vessel.

Figure 5 shows the test set up for a PT415 cooler that was tested in June 2015. Figures 6a and 6b show a smaller cooler at Cryomech that had already been tested. The photos in Figures 6a shows the copper shield attached to the first stage cold head after the outer MLI was removed. The photo in Figure 6b shows the MLI that covers the second stage pulse tube, regenerator tube and the second stage cold head to prevent radiation shine between the first stage and shield and the second stage.



Figure 5. The PT415 cooler test setup at Cryomech. The compressor is on the left. The cooler cold head and vacuum vessel are to the right. Twenty meters of line connecting the compressor on the left to the cooler cold head on the right is coiled up to the left of the PT415 compressor.



Figure 6. a) The cooler shield connected to the 1st stage and b) the MLI inside of the shield

For tests done at Cryomech in June of 2015, there were heaters capable of generating up to 100 W were attached to both stages of the coolers. During the cooler extended characteristic test done at Cryomech in 2006, there were heaters on both stages that could generate up to 250 W. The heaters must be firmly attached to the cooler stage cold heads. The temperature sensors must be firmly mounted to the cold heads in a location that is well away from the heaters. The temperature sensors connect to the cooler colds must be fully calibrated over a temperature range from 2 K to 400 K. Cryomech uses Scientific Instruments fully calibrated silicon diode sensors. Since there is no magnetic field, this sensor is a good choice. Cernox sensors can be used as well as long as they are fully calibrated over a temperature range similar to the silicon diode sensors. The temperature sensor wires must be thermally connect to the cold heads.

The heaters are controlled by a controller that keeps the heater power constant to within 0.01 W. The temperatures of both cold heads are measured every second. The pulse tubes in the PT415 cooler pulse at the rate of 1.2 Hz. This pulse rate is independent of the line frequency. Unlike most coolers, the refrigeration on both cold heads is independent of the line frequency. The temperature on the cold heads pulses at the rate of 1.2 Hz. The temperature pulsation is quite evident at low temperatures. The cold head temperatures should be time averaged over several minutes. At low temperatures on the 2nd-stage cold head temperature peak-to-peak amplitude can be as high as 0.6 K. Figure 7 shows the temperature oscillations on the cooler second stage. Figure 8 shows the measured peak-to-peak amplitude as a function of 2nd-stage heat load Q2 as two different 1st-stage heat loads Q1. To first order, the 2nd-stage temperature T2 is proportional to the 2nd-stage heat load Q2 at Q2 less than 40 W.



Figure 7. The transition between a 15 W heat load and a 10 W heat load on the cooler 2nd-stage. In 30 minutes, the cooler pulses 2160 times. The average cold head T is at the center of the band.

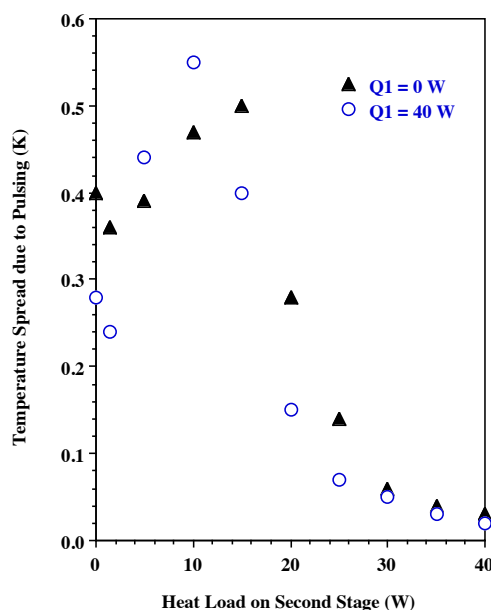


Figure 8. A plot of the amplitude (peak-to-peak) versus the second-stage heat load for 1st-stage heat loads Q1 of 0 and 40 W.

The temperature amplitude of the pulse increases in amplitude from 4 K to about 10 K. The amplitude of the temperature pulsation is larger at 2.7 K than it is at 4.2 K. As the temperature increases above 10 K the amplitude of the pulse decreases rapidly. This is a manifestation of the increased specific heat of the cold head with respect to that of the helium gas. The increased pulsation amplitude between 4.2 K and 2.7 K may reflect an increase in the specific heat of the helium gas. The authors do not have an explanation for the temperature oscillation amplitude behavior as a function of 1st-stage heat load Q1.

4. PT415 Cooler Performance Graphs over Various Temperature Ranges

This section presents the operating parameters for the PT415 cooler. The operating parameter data is for three different coolers. The performance of any type of cooler is not exactly the same from cooler to cooler. This is true for coolers from all of the small cooler manufacturers. Some components in small coolers are hand made. Each cooler is packed with regenerator material by hand. Variations of the helium pressure in the hoses between the cold head and the compressor affects the cooler operating performance on both stages. Each cooler has its own personality and its own sweet spot where the cooler works the best.

Figure 9 shows the temperature map for a PT415 cooler measured by Florida State University [16]. Similar measurements were made by Cryomech [17] in 2006, but these measurements didn't cover as much of the operating space as the FSU measurements. Figure 9 shows the temperature map for first-stage heat loads from 0 to 84 W combined with second stage heat loads from 0 to 3 W. Having the FSU temperature map proved invaluable in determining what went wrong with the MICE spectrometer solenoids [18].

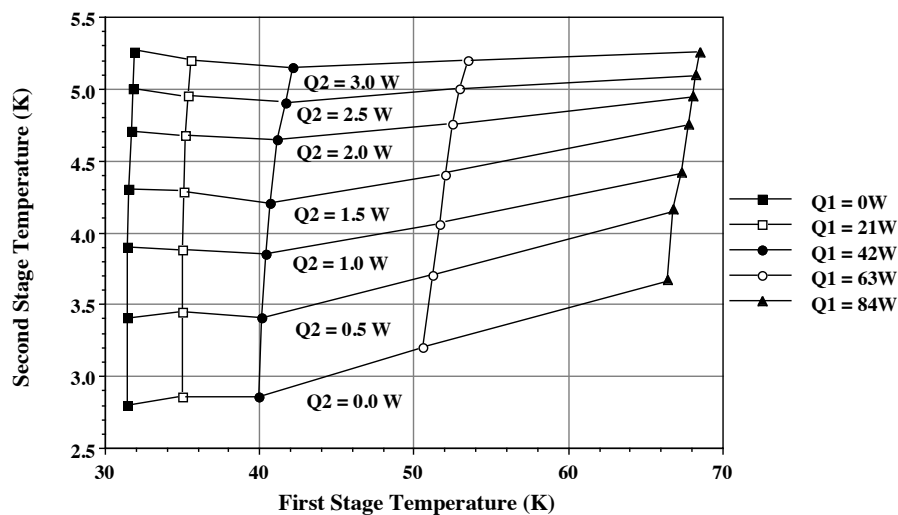


Figure 9. PT415 temperature map as a function of Q1 from 0 to 84 W and Q2 from 0 to 3W [16].

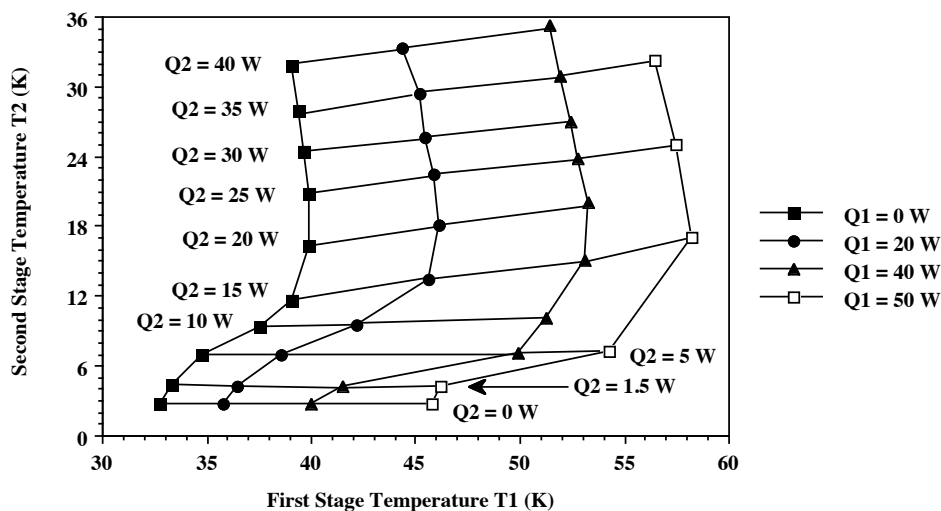


Figure 10. PT415 temperature map as a function of Q1 from 0 to 50 W and Q2 from 0 to 40 W.

Figure 10 shows an extended temperature map measured in June 2015 at Cryomech. This map covers temperatures from 0 to 36 K on the second-stage cold head and 30 to 60 K on the first-stage cold head. The temperature map in Figure 10 was measured with a heat load Q_1 on the first-stage from 0 to 50 W while a heat load Q_2 was applied on the second-stage from 0 to 40 W. The parameter space was extended to Q_2 up to 80 W for a Q_1 between 0 and 40 W, but that is not shown in figure 10. The temperature map shown in Figure 10 is very useful for applications in the liquid hydrogen range (from a triple point temperature at 13.8 K and a critical temperature of 32.2 K for para-hydrogen) such as are found in the MICE hydrogen absorbers [9] or in a liquid hydrogen-cooled magnet [8].

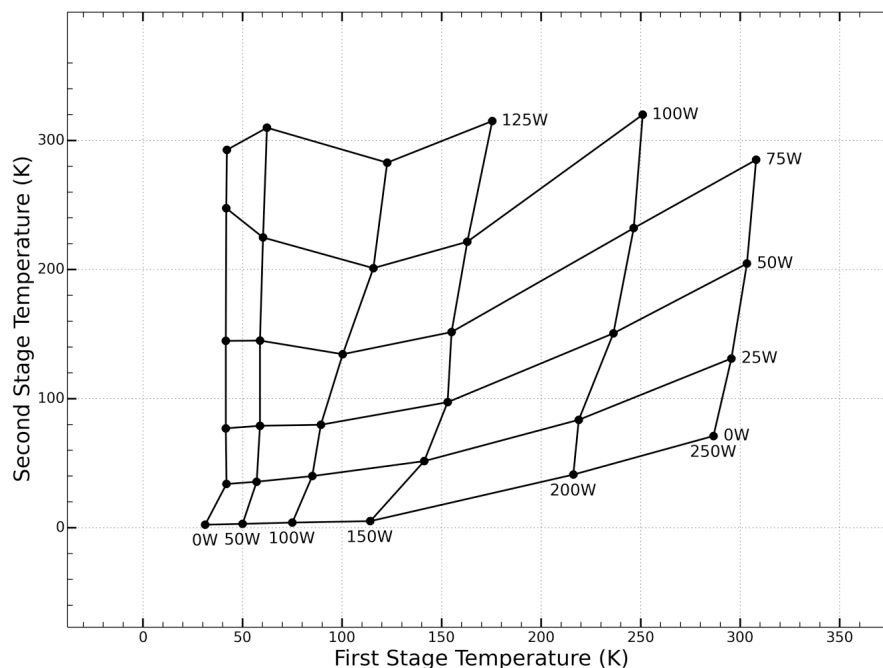


Figure 11. PT415 temperature map as a function of Q_1 from 0 to 250 W and Q_2 from 0 to 125 W.

Figure 11 above includes the temperature range from absolute zero to room temperature on both of the PT415 cooler stages. The cooler map shown in Figure 11 is useful for determining the cool-down behavior of a PT415 cooler. The data from Figure 11 and Figure 10 would be useful for improving the cool-down model for the cyclotron gas-stopper magnet at MSU [7], [15].

5. Concluding Comments

The data that is in this paper provides a more complete picture of the operating parameters of the PT415 cooler and its remote motor cousin the PT415-RM cooler, which has ninety percent of the cooling of the PT415 cooler on both cold heads. Having more than one temperature map of a cooler such as the PT415 cooler is important in understanding the behavior of a piece of apparatus that has one or more coolers installed within it. The caveat is that one must have fully calibrated temperature sensors firmly attached to the cooler cold heads, in a helium bath (if there is one) and in key places on the apparatus being cooled-down and being kept cold using the coolers. The temperature sensors must be accurate under the operating conditions of the device being cooled. If there is liquid helium in the apparatus, a measurement of the vapor pressure of the helium is a useful check.

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