Proposed Rapid Cooldown Technique for Pulse Tube Cryocoolers

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ABSTRACT

Some cryocooler applications, such as those for military operations dealing with high temperature superconducting (HTS) magnets, motors, or generators, require faster cooldown times than what can normally be provided with a cryocooler designed to accommodate a relatively small steady-state heat load. The current approach to achieve fast cooldown is to use a cryocooler oversized for steady-state operation. This paper proposes a new method applicable only to pulse tube cryocoolers that may decrease cooldown times by a factor of two or three when cooling to temperatures in the range of 50 K to 80 K from room temperature without increasing the size of the cryocooler. Such temperatures are appropriate for HTS magnets, generators, or motors. The proposed method makes use of the resonance phenomenon that occurs with an appropriately sized combination of inertance tube and reservoir volume. With a small reservoir, an *LC* resonance effect can occur at typical operating frequencies, with *C* being the compliance (volume) of the reservoir and inertance tube and *L* being the inertance of the inertance tube. At or near resonance the input acoustic impedance to the inertance tube is low, which allows for a high acoustic power flow at the cold end of the pulse tube for a given pressure amplitude. When the reservoir volume is increased to its normal size, the impedance increases to the value optimized for steady-state operation. A simple ball valve can then be used to change the reservoir volume and to switch from the fast cooldown mode to the steady-state mode. The higher acoustic power flow can be accommodated by the pulse tube and regenerator when they are at or near room temperature. In most cases the higher acoustic power in the fast cooldown mode does not require additional input power to the pressure oscillator because the load impedance is a closer match to that of the oscillator compared to that of the normal load during cooldown.

INTRODUCTION

Cryocoolers for use in military operations often need to cool quickly to the operating temperature to enable rapid deployment. The system of particular interest here is the cooling of a 3 T high-temperature superconducting magnet for use in a gyrotron to generate high-power millimeter waves at a frequency of 95 GHz. Such waves can be used as a non-lethal method for repelling personnel in crowd control. This system is known as the active denial system (ADS).[1] To be operational the magnet must be cooled to the design temperature, which for a magnet made with YBCO (second generation high-temperature superconducting wire), is a temperature of

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about 50 to 60 K. The mass of a YBCO magnet for this application is about 20 kg. Typically the cooldown time for this mass may be about 16 hours when a cryocooler designed for high efficiency and low mass is used. For the active denial system considered here cooldown times less than four hours are often desired. The net refrigeration power required at 50 K to maintain the magnet at 50 K is estimated to be 50 W. The cooldown time is inversely proportional to the refrigeration power provided by the cryocooler over the entire temperature range from ambient down to the operating temperature. Typically, the net refrigeration power available at room temperature is much larger than that available at the cold operating temperature, partly because the thermal losses, such as conduction, radiation, and regenerator ineffectiveness are zero or very small at room temperature.

To decrease the cooldown time the net refrigeration power should be increased beyond that normally available over the whole temperature range. However, the size and mass of the system will depend on the maximum net refrigeration power the system can provide at the cold operating temperature. The PV power provided by the compressor is highest when the cold end is at its lowest temperature, even though the net refrigeration power is higher at the higher temperatures. Ideally we need to find some method for increasing the net refrigeration power at the higher temperatures without increasing the size and mass of the system, and still keeping the input power less than the maximum capability of the compressor. For Gifford-McMahon and rotary Stirling cryocoolers an increased speed at the higher operating temperatures can be used to provide a faster cooldown time. For Stirling and pulse tube cryocoolers using linear-resonant pressure oscillators (compressors) the speed cannot be increased significantly because the off-resonant condition of the compressor would lead to low efficiency. We describe here a method that should allow the cold head of a pulse tube cryocooler driven by a linear-resonant compressor to accept nearly the full PV power output of a compressor over the entire temperature range of the cold end. As a result, the cooldown time may be decreased by a factor of two or three compared with that of a pulse tube cryocooler not utilizing the fast cooldown technique.

COOLDOWN TIME

Thermodynamics

The first-law energy balance for the cold end of a cryocooler is given by

$$\dot{Q}_{net} = -mc_p \frac{dT}{dt}, \tag{1}$$

where m is the mass of the object being cooled, c_p is the specific heat of the object, T is temperature and t is time. The incremental cooling time per unit mass is then given as

$$-\frac{dt}{mdT} = \frac{c_p}{\dot{Q}_{net}}. \tag{2}$$

The cooldown time Δt per unit mass to reach T_2 (50 K) from a starting temperature of T_1 (300 K) is found by integrating Eq. (2) to obtain

$$\frac{\Delta t}{m} = \int_{T_2}^{T_1} \frac{c_p}{\dot{Q}_{net}} dT. \tag{3}$$

For the examples to be considered here we assume the mass to be cooled to have the specific heat of stainless steel, as shown in Fig. 1, a major component of composite YBCO tape.

Example with Gifford-McMahon Cryocooler

The load curve of a typical Gifford-McMahon (GM) cryocooler[2] that meets the 50 W net refrigeration requirement is shown in Fig. 2. The input power is 7.5 kW, and the mass of the complete cryocooler system (including compressor) is 138 kg. The ratio of specific heat to the

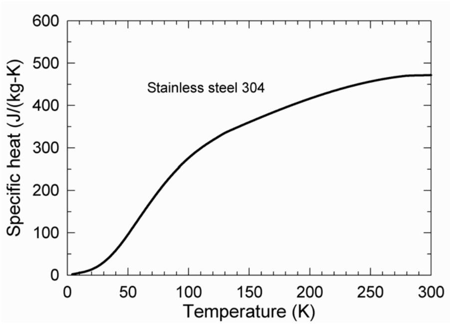

Figure 1. Specific heat of stainless steel 304.

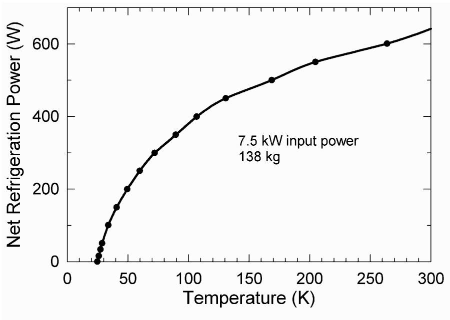

Figure 2. Load curve of a typical Gifford-McMahon cryocooler that provides 200 W at 50 K.

net refrigeration power of this GM cryocooler is shown in Fig. 3. The average value over the temperature range from 50 to 300 K is shown as a dashed line in this figure and gives a cooldown time of about 1 hr for the 20 kg of stainless steel.

Example with Stirling Cryocooler

The load curve of a lightweight Stirling cryocooler[3] is given in Fig. 4. Though the no-load temperature is about 50 K, we use this example to illustrate certain features of cryocoolers using linear resonant compressors. The net refrigeration power of this cooler at 60 K is about 10 W, which means that about five of these coolers would be required to provide 50 W at 60 K. Ideally one cryocooler with five times the cooling power would be used. The input power would then be about 1500 W and the cooler mass would be somewhat less than 45 kg. Figure 5 shows the cooling time for stainless steel with one of these cryocoolers. A cooldown time to 60 K for 20 kg of stainless steel is indicated in the figure to be 10.7 hours. For a cooler with five times the cooling capacity the cooldown time would be 2.1 hours.

Though this cryocooler cannot provide the necessary cooling power at 50 K, we show this example to illustrate some qualitative features about the input power of regenerative cryocoolers. Figure 6 shows the input power for this cryocooler as a function of the cold-end temperature. We note that even though the input power is 300 W when the cooler is cold, the input power is only about 170 W when the cold tip is at room temperature. This reduced input power at warmer temperatures is characteristic of regenerative cryocoolers and is explained in the next section.

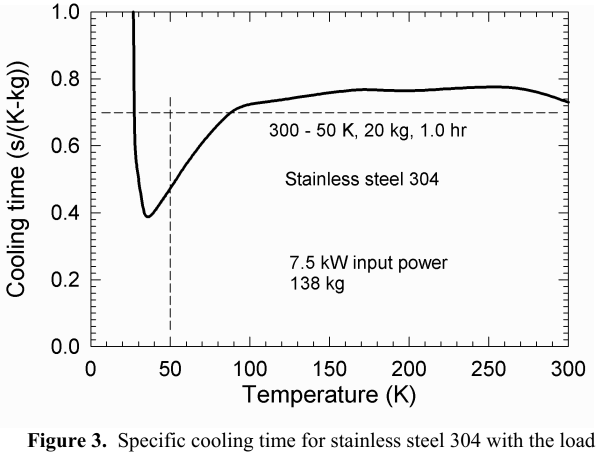

Figure 3. Specific cooling time for stainless steel 304 with the load curve of the Gifford-McMahon cryocooler shown in Fig. 2.

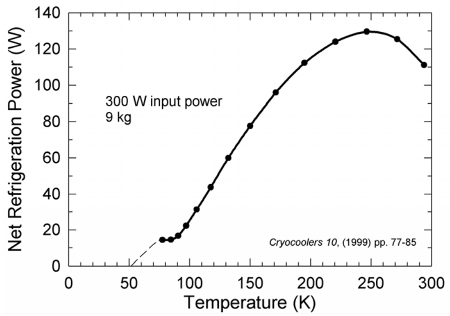

Figure 4. Load curve of a light weight Stirling cryocooler.

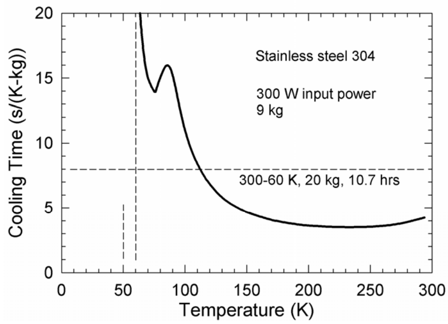

Figure 5. Specific cooling time for stainless steel 304 with the load curve shown in Fig. 4.

Pulse Tube Cryocooler Model

A pulse tube cryocooler was modeled with the NIST software REGEN3.2[4] to optimize the regenerator and a transmission line model for the inertance tube.[5,6] The operating frequency is 60 Hz with an average pressure of 2.5 MPa and a pressure ratio at the cold end of 1.3. The optimum impedance of the inertance tube provided a phase of 60° (pressure leading flow) at the warm end of the pulse tube, and the optimum pulse tube volume forced the phase to be 30° at the cold end of the regenerator. Figure 7 shows the calculated net refrigeration power as a function of temperature with the cold end PV power being fixed at 230 W independent of the cold-end temperature. With this PV power a net refrigeration power of at least 50 W at 50 K is achieved. As this figure shows, the net refrigeration power increases with temperature because the losses decrease at higher temperatures. Figure 8 shows the calculated specific cooling time with this pulse tube cryocooler. A 20 kg mass of stainless steel would be cooled to 50 K in about 3.1 hrs with this model refrigerator that requires an input power of about 2.0 kW. The cryocooler mass is estimated to be about 50 kg if reasonable effort is made to minimize the mass.

REFRIGERATION POWER AND INPUT POWER

Net Refrigeration Power

The net refrigeration power of a cryocooler is given by

$$\dot{Q}_{net} = \dot{Q}_{gross} - \dot{Q}_{losses}, \tag{4}$$

where $\dot{Q}_{gross}$ is the gross refrigeration power and $\dot{Q}_{losses}$ is the sum of all the thermal losses, such as radiation, conduction, regenerator ineffectiveness, and expansion irreversibilities. These losses are small when the cold tip is at ambient temperature, but increase as the temperature of

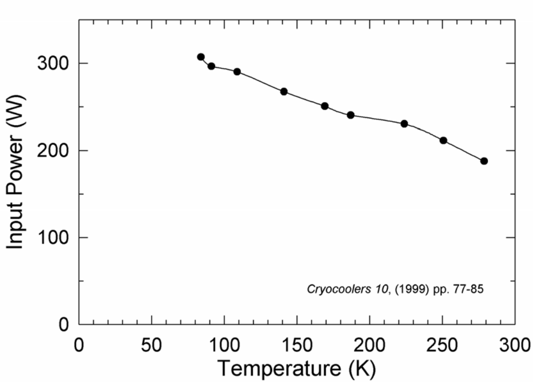

Figure 6. Input electrical power for same cryocooler as for Fig. 4.

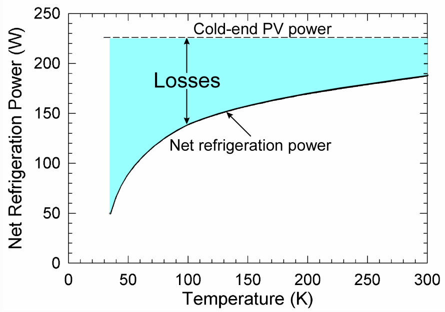

Figure 7. PV power, losses, and net refrigeration power calculated for the model pulse tube cryocooler.

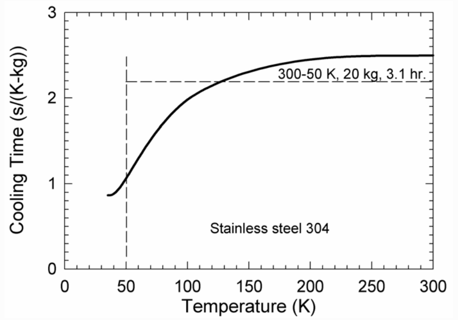

Figure 8. Specific cooling time for the model pulse tube cryocooler.

the cold tip decreases. The gross refrigeration power for a Stirling or Gifford-McMahon (GM) cryocooler is simply the PV power of the displacer, which is equal to the acoustic power flow in the working fluid at the cold end. For the pulse tube cryocooler the gross refrigeration power is also equal to the acoustic power flow at the cold end.[7] Thus, for regenerative cryocoolers the gross refrigeration power can be given by

$$\dot{Q}_{gross} = \left\langle P_d \dot{V} \right\rangle_c , \tag{5}$$

where P_d is the dynamic pressure, $\dot{V}$ is the volume flow rate, the $\langle\ \rangle$ brackets indicate a time averaged value over one cycle, and the subscript c refers to the cold end. For Stirling and GM cryocoolers the displacer operating at a given frequency determines the volume flow rate. Because the displacer is designed to be at nearly full stroke when operating cold, there is no way to increase the flow rate beyond the design value, unless the speed is increased, which can be done only in GM cryocoolers or Stirling cryocoolers that are not using a linear-resonant compressor. When the cold tip is warm the dynamic pressure in Stirling or Stirling-type pulse tubes will increase some, but we will ignore that small effect in our analysis here.

In Stirling-type pulse tube cryocoolers where a fixed orifice or inertance tube is used to provide the optimum flow rate when the cold end is cold, the cold-end volume flow will not change when the cold end is at 300 K because the flow impedance (orifice or inertance tube) is always at 300 K (at least for a single-stage cooler). However, the goal of this paper is to show how this impedance can be changed very easily to allow for an increased flow and PV power at the cold end of the pulse tube. This method is discussed in a later section.

Input PV Power

During normal operation with the cold tip at some low temperature, the temperature gradient in the regenerator causes the ideal input acoustic power and compressor PV power to be higher than that at the cold end by the ratio

$$\frac{\left\langle P_d \dot{V} \right\rangle_h}{\left\langle P_d \dot{V} \right\rangle_c} = \frac{T_h}{T_c} , \tag{6}$$

where T_h is the hot temperature and T_c is the cold temperature. The ratio increases when pressure drop in the regenerator is taken into account. Equation (6) shows that when the cold end is at 300 K the input PV power will be the same as that at the cold end when pressure drop is ignored. Because the PV power at the cold tip is limited by the displacer stroke or the impedance in the pulse tube cryocooler, the input PV power with the cold end warm will be much less than the input power when the cold end is cold. For a normal operating temperature of 50 K the ideal input power will be reduced by a factor of six when the cold end is at 300 K.

Input Electrical Power

The conversion of electrical input power to PV or acoustic power is accomplished in the compressor with some efficiency. The efficiency can be high (near 80 %) when the flow impedance of the load matches that of the compressor (compressor operating at its resonance condition), but it can be much less when the impedances are not matched. The flow impedance of the cryocooler or compressor is given by

$$\boldsymbol{Z} = \frac{\boldsymbol{P}}{\dot{\boldsymbol{V}}}, \tag{7}$$

where the bold symbols indicate the variables are time dependent and can be represented by sinusoidal or complex variables. A cryocooler is normally optimized to have its input impedance match that of the compressor when the cryocooler is cold. When the cold end is warm the input impedance of the cryocooler is significantly increased because of the lower input flow rate indicated by Eq. (6). When starting from 300 K, the mismatched load causes the compressor efficiency to be significantly lower than when the cold tip reaches its normal operating temperature. Thus, the actual input power during startup may only be slightly less than the value when the cold end is at 50 K, even though the input PV power is about six times less according to Eq. (6). Figure 6 shows the input electrical power of the Stirling cryocooler discussed earlier. As indicated in this figure the input electrical power is somewhat reduced when the cold end is warm, but not as much as the temperature ratio would suggest for the PV power. This impedance mismatch during startup significantly limits any increase in PV power that could be delivered to the cold end even if the cold end could accept more flow.

ADJUSTABLE FLOW IMPEDANCE

Inertance Tube

With Stirling-type pulse tube cryocoolers operating at relatively high frequencies an inertance tube is used to obtain the optimum impedance.[7] The transmission line model can be used to obtain the impedance of the inertance tube.[5,6] Typically the phase of the optimum impedance at the inertance tube entrance is about 60°. To achieve such a phase the reservoir volume at the end of the inertance tube is normally made rather large compared with the volume of the inertance tube, although for acoustic power flows greater than about 100 W it is possible to achieve such a phase even with zero reservoir volume as long as the inertance tube volume is made sufficiently large. We have shown previously that the impedance of the inertance tube can be varied significantly by the size of the reservoir volume.[8] As a result, the acoustic power at the inlet to the inertance tube for a fixed pressure amplitude can be varied considerably by varying the reservoir volume. Figure 9 shows this variation of acoustic power with reservoir volume for

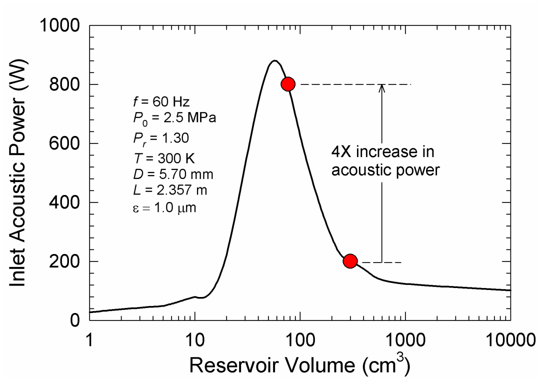

Figure 9. Acoustic power at the inlet to the inertance tube vs. the reservoir volume for the model pulse tube cryocooler.

the pulse tube model considered here. With a volume of 300 cm^3 the acoustic power according to the transmission line model is shown to be 200 W and the phase of the impedance is 60°. As the reservoir volume is reduced the acoustic power is increased and reaches a maximum of about 900 W for a reservoir volume of about 60 cm^3. With that volume the impedance reaches a minimum and the phase becomes zero. Such a condition represents a resonant effect in the system analogous to a *LC* resonance in an electrical system. Here *L* is analogous to the inertance of the inertance tube and *C* is analogous to the compliance of the inertance tube and reservoir volume.

Variable Reservoir Volume

As shown in Fig. 9 the acoustic power at the inlet to the inertance tube can be increased from 200 W to 800 W by changing the reservoir volume from 300 cm^3 to about 75 cm^3, an increase by a factor of four. With the smaller reservoir volume the phase of the impedance is decreased to about 10°, which is much less than the optimum phase for the case when the system is cold. However, when the system is warm such a phase is close to an optimum for the regenerator and for an impedance match with the compressor, as will be shown later. Thus, we propose that a faster cooldown time can be achieved by using the simple arrangement shown in Fig. 10. During startup when the system is at 300 K the valve between the two reservoirs is closed so that the reservoir volume seen by the inertance tube is volume #1, which for this case is about 75 cm^3. The high acoustic power flow into the inertance tube causes the acoustic power at the cold end to increase with a subsequent increase in the net refrigeration power when the system is warm. The regenerator and the pulse tube are not designed to accommodate the high power flow during normal operation at the low temperatures, but at high temperatures where the losses are small, the net refrigeration power is significantly increased by the higher acoustic power flow. When the cold end reaches some low temperature (about 100 K in this example) the valve is opened to the larger reservoir #2 (225 cm^3) so that the total reservoir volume seen by the inertance tube becomes 300 cm^3. With that volume the system has the optimum impedance for operation at 50 K. The valve shown in Fig. 10 should be a ball or plug valve that offers a low flow resistance when it is open. If desired, the valve could be electrically controlled to allow for automatic operation at the optimum temperature of the cold end.

RAPID COOLDOWN

Calculated Cooldown Time

Figure 11 shows the cold-end PV (acoustic) power and the net refrigeration power when the rapid cooldown procedure is used for temperatures down to 100 K before switching to the normal configuration with the lower PV power. Figure 12 shows the cooling time under this mode of operation. The calculated cooldown time to 50 K for the 20 kg of stainless steel is shown to be about 1.6 hrs as opposed to 3.1 hrs without using the rapid cooldown technique. The use of another valve and reservoir volume could be used to decrease the cooldown time

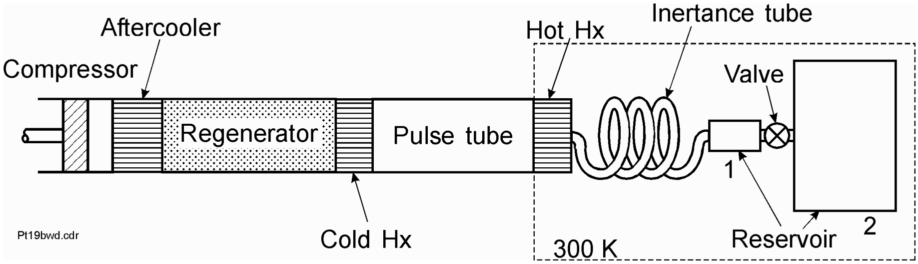

Figure 10. Schematic of a pulse tube cryocooler with two reservoirs and a control valve that is closed to give a small impedance of the inertance tube and provide for fast cooldown.

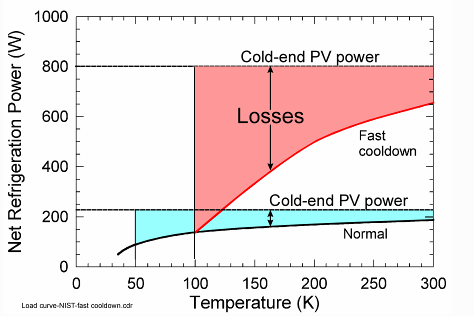

Figure 11. PV power, losses, and net refrigeration power calculated for fast and normal cooldown processes.

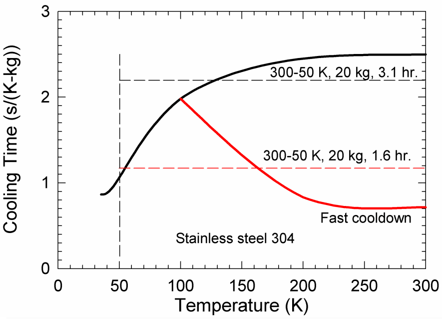

Figure 12. Specific cooling times for the model pulse tube cryocooler calculated for fast and normal cooldown processes.

further, but the gain will not be so large. Ideally, an infinitely variable reservoir volume could be used, but the practical problems may not warrant such a refinement.

Compressor Impedance Matching

The flow impedance of the model pulse tube cryocooler as given by Eq. (7) at the inlet to the aftercooler when the system is at its normal operating temperature of 50 K is 41.7 MPa·s/m^3 at a phase of -39.2°(pressure lagging flow). We assume that a compressor designed to drive this model pulse tube cryocooler would have the maximum efficiency (resonance) at this same impedance. A representative impedance map[9] showing contours of compressor efficiency for such a linear-resonant compressor is shown in Fig. 13. Because such a compressor was designed for this particular load at 50K, the efficiency is shown to be at the highest value of about 80 %. The PV power at the cold end is calculated to be about 233 W and that at the warm end is 1742 W. If the system is started at 300 K under normal conditions with the same reservoir volume, the load impedance at 300 K is calculated to be 111.4 MPa·s/m^3 at a phase of -61.6°. This considerably higher value of impedance forces the compressor to be operating far removed from its resonant condition and reduces the compressor efficiency to about 60 %, as shown in Fig. 13. When the small reservoir is used for a rapid cooldown, the impedance at 300 K is 45.6 MPa·s/m^3 at a phase of -54.7°, which is much closer to the optimum value, as shown in Fig. 13. Thus, the compressor will have nearly its same high efficiency at startup as it has during steady-state operation at the cold temperature. Figure 14 shows the variation of the input PV power and the estimated input electrical power (assuming a compressor efficiency of 80 % at the optimum load impedance) with the cold end temperature for both the normal cooldown procedure and the fast

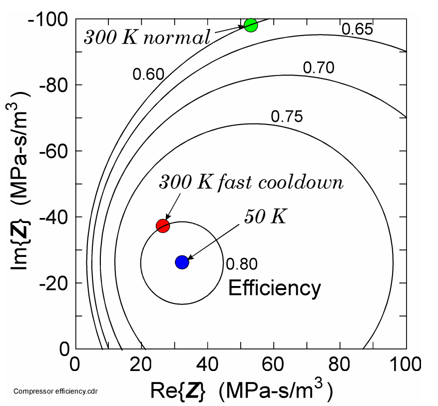

Figure 13. Estimated impedance map of compressor.

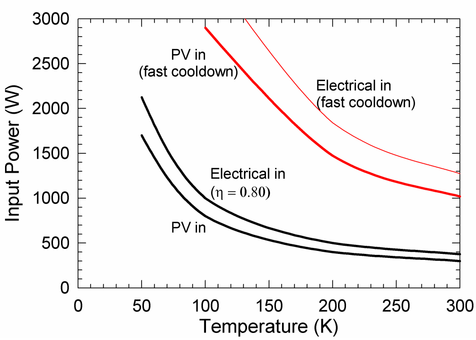

Figure 14. PV and electrical input power for compressor during normal and fast cooldown procedures, assuming a compressor efficiency of 80 % for both cases.

cooldown procedure. The fast cooldown procedure allows the compressor to output much more PV power under high efficiency conditions. As Fig. 14 shows the input electrical power exceeds 3000 W at a temperature of 130 K, which may be over the maximum rated power of the compressor. Thus, it may be necessary to switch to the large reservoir at 130 K instead of 100 K. Ideally, the use of another valve and intermediate reservoir could be used at this temperature to maintain a relatively fast cooldown.

CONCLUSION

We have shown that the cooldown time for pulse tube refrigerators designed to cool a superconducting magnet to 50 K with 50 W of net refrigeration power can be decreased by a factor of two or more by increasing the acoustic power flow at the cold end during startup when losses are small. The acoustic power is reduced to the design value when the temperature reaches about 100 K. Normally the acoustic power at the cold end in regenerative cryocoolers is a fixed value determined by the displacer stroke in a Stirling or GM cryocooler, or by the impedance of the inertance tube in a pulse tube cryocooler. The impedance of the inertance tube can be changed by varying the volume of the reservoir attached to the end of the inertance tube. For the pulse tube cryocooler modeled here the optimum impedance allowed 200 W of acoustic power at the cold end when the pressure ratio in the system was 1.3. The inertance tube provided a phase shift of 60° under these conditions and used a reservoir volume of 300 cm^3. By decreasing the reservoir volume to about 75 cm^3 during startup from 300 K, the inertance tube/reservoir volume combination is close to a *LC* resonance condition that leads to a reduction in the impedance and an increase in the acoustic power through the inertance tube. This power is increased to about 800 W, which leads to a large increase in the net refrigeration power at 300 K and a faster cooldown. For 20 kg of stainless steel the normal cooldown time calculated for this pulse tube cryocooler model is 3.1 hours, but the rapid cooldown technique described here results in a cooldown time to 50 K of 1.6 hours. We have also shown that during normal cooldown there is a large impedance mismatch with the compressor that causes a low compressor efficiency during the initial stages of the cooldown. The rapid cooldown technique described here maintains a better impedance match to the compressor, which maintains a rather high compressor efficiency even at startup. The total input electrical power at startup with the rapid cooldown technique is still less than the 2000 W steady-state value required when the cold end has reached 50 K and the impedance is set to the design value.

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