**A 63 K phase change unit integrating with pulse tube cryocoolers**

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**Abstract.** This article presents the design and computer model results of an integrated cooler system which consists of a single stage pulse tube cryocooler integrated with a small amount of a phase change material. A cryogenic thermal switch was used to thermally connect the phase change unit to the cold end of the cryocooler. During heat load operation, the cryogenic thermal switch is turned off to avoid vibrations. The phase change unit absorbs heat loads by melting a substance in a constant pressure-temperature-volume process. Once the substance has been melted, the cryogenic thermal switch is turned on, the cryocooler can then refreeze the material. Advantages of this type of cooler are no vibrations during sensor operations; the ability to absorb increased heat loads; potentially longer system lifetime; and a lower mass, volume and cost. A numerical model was constructed from derived thermodynamic relationships for the cooling/heating and freezing/melting processes.

**1. Introduction**

Several important aims of mechanical cryocoolers are to reduce levels of vibration, electromagnetic disturbance and the ability to absorb peak heat loads to meet performance goals [1]. However, mechanical cryocoolers with no vibration, no electromagnetic disturbance are still a challenge today. To deal with these competing factors, cryogenic phase change systems have been proposed as a potential solution. To provide the benefits, phase change units embedded within phase change materials must undergo a phase transition [2-3]. Trade studies indicate that phase transitions that occur with constant pressure-temperature-volume process require the least weight and volume. Thus, phase change materials that undergo melt are the working fluids of choice for integrated cooler system. This paper will describe a working fluid (nitrogen), system design methodology that enables nearly all of the above criteria to be met. The objective of this paper is to develop an integrated cooler system that operates near 63 K. This paper details the progress made toward the objective and covers the design
and calculations of the pulse tube refrigerator, the thermal switch and the phase change unit. A simple computer model together with its numerical results is shown. Ideas for experiment results with integrated cooler system will appear in a future paper.

2. System design

2.1. The integrated cooler system

Figure 1 shows the general scheme of integrated cooler system. The figure depicts the heat load that has to be cooled, the phase change unit, the thermal switch and the pulse tube refrigerator. During the charge phase of the phase change unit, this switch should conduct heat well. In contrast, the switch should have a large thermal resistance when the pulse tube refrigerator is switched off, so as to reduce the heat load to the phase change unit.

![Figure 1. Scheme of the integrated cooler system.](image)

2.2. The pulse tube refrigerator

Current researches and applications of pulse tube refrigerator operating around 60 K temperature region is relatively mature [4,5]. Producers all around the world have launched a series of products. Table 1 gives the key development goals of the high capacity single-stage 60 K PTC. The coaxial arrangement is adopted to ease the complexity of system integration and to reduce the cost. It is required to provide at least 2.0 W of net cooling power at 60 K with an input power of less than 75 W into the compressor at 300 K reject temperature. The overall mass should be kept below 10 kg.

| Parameters                    | Design goal     |
|-------------------------------|-----------------|
| Geometrical arrangement       | Coaxial         |
| Cooling capacity              | 2.0 W@60 K      |
| Reject temperature            | 300 K           |
| Relative carnot efficiency    | >10%            |
| Mass                          | <10 kg          |
| Power consumption             | <75 W           |
To minimize the mass and power consumption, the swept volume of the pulse tube refrigerator should be smaller and the motor efficiency of the compressor needs to be higher. The design of the pulse tube refrigerator was completed through SAGE. Table 2 is a detailed design parameters of the pulse tube refrigerator.

Table 2. Detailed design parameters of the pulse tube refrigerator.

| Parameters                  | Calculated values |
|-----------------------------|-------------------|
| Swept volume of compressor  | 7.0 cc            |
| Regenerator matrix          | 400#SS            |
| Connecting tube             | Φ5.5 mm×15 cm     |
| Diameter of regenerator     | Φ26 mm×74 mm      |
| Filling pressure            | 3.5 MPa           |
| Resistance tube             | Φ3.0 mm×1.2 m+Φ5.0 mm×2.0 m |
| Operating frequency         | 60 Hz             |
| No-load temperature         | 41.3 K            |
| Power consumption           | 70.625 W          |
| Relative carnot efficiency  | 11.33%            |
| Gas reservoir volume        | 480 cc            |
| Pulse tube                  | Φ14.4 mm×80 mm    |

2.3. The thermal switch

The thermal switch used in this system is designed at temperatures ranging from 60 K to 300 K that is based on the differential thermal expansion of two materials (copper and Teflon). Figure 2 shows the schematic of the switch with three main parts: cold section, warm section and Teflon rod. The sections are separated by a Teflon rod. The cold section is directly mounted to the pulse tube refrigerator and a narrow, flat copper-copper gap is created. When the cold side of the thermal switch is cooled, the different contraction of the sections and Teflon rod makes the gap between two sections decrease.
When the gap is zero or below zero, the thermal switch is coupled to allow heat to be transferred to the pulse tube refrigerator. During the continued cooling of the thermal switch, the thermal contact resistance at the section's interfaces decreases, decreasing the total thermal resistance of the switch.

2.4. The phase change unit

Figure 3 shows the general scheme of the phase change unit. Many existing phase change unit designs are aimed at absorbing peak loads allows for the reduction of the cooler mass and power consumption. The possibility of heat load operation without cooler interference, which is achieved by turning the cryocooler off, is acknowledged as an advantage as well.

In this design, a phase change unit that is attached to the cooler (via a heat switch) is filled with liquid nitrogen. When the triple-point is reached the pressure and temperature stabilise at 12.5 kPa and 63.15 K, respectively. This stable point is maintained until all liquid nitrogen is transformed to solid nitrogen. The heat leak of the phase change unit includes the heat load, the heat leak through the thermal switch, the phase change unit container and the connecting tube. Based on the calculation, the phase change unit should be able to contain about 0.45 l of nitrogen which corresponds to a phase change unit capacity of 7.2 kJ (or 2 Wh).

![Figure 3. Scheme of the phase change unit.](image)

3. Computer model

The cooling/heating and freezing/melting processes can be explained by a simple model that is based on derived thermodynamic relationships(Table 3). It consists of the phase change unit with heat capacity $Q = mC\Delta T$. The phase change unit is thought of as a heat load that is connected to the pulse tube refrigerator through a thermal resistance $R = Q_{\text{load}} + Q_{\text{heat-leak}}$. This thermal resistance may be considered as a combination of the heat load, the heat leak through the thermal switch, the phase change unit container and the connecting tube. Figure 4 shows the cooling/freezing processes of the calculated system, From figure 4, it can be concluded that the pulse tube refrigerator designed in this
paper is suitable. Figure 5 shows the heating/melting processes of the calculated system. From figure it can be concluded that the capacity of the phase unit (2 Wh) is met. Also, the results in figure 5 show that the capacity of the phase change unit increases with the rise of heat load. And, if the sensible heat of the nitrogen was used, the capacity of the phase change unit could be increased to 2.75 Wh.

Table 3. Equations describing the thermodynamic relationships.

| Processes  | Equations                                      |
|-----------|------------------------------------------------|
| Cooling   | \((Q_0 - Q_{\text{load}} - Q_{\text{heat-leak}})t = mC\Delta T\) |
| Freezing  | \((Q_0 - Q_{\text{load}} - Q_{\text{heat-leak}})t = m\Delta H_{\text{melt}}\) |
| Melting   | \((Q_{\text{load}} + Q_{\text{heat-leak}})t = m\Delta H_{\text{melt}}\) |
| Heating   | \((Q_{\text{load}} + Q_{\text{heat-leak}})t = mC\Delta T\) |

Figure 4. The cooling/freezing processes of the calculated system.

Figure 5. The heating/melting processes of the calculated system.
4. Conclusion
An integrated cooler system has been designed. In order to meet the requirements, the heat load has to be significantly reduced. The large improvement is achieved by introducing the heat switch. The system design methodology that enables nearly all of the criteria to be met has been showed in this paper. The design calculations and numerical results show that the primary objective of this integrated cooler system has been met.

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