Cryocoolers for Microsatellite Military Applications

Erin Pettyjohn

Air Force Research Laboratory, Space Vehicles Directorate
Kirtland Air Force Base, NM

ABSTRACT

Space qualified cryocoolers have been extensively developed for large military and commercial satellite electro-optical (EO) infrared (IR) missions, but not so for microsatellites due to the complexity of the thermodynamics and fluid mechanics of the mechanical refrigeration system. The trend in military responsive space programs is leaning towards microsatellites that are cheaper and faster to build and launch. No longer can cryocoolers take 3-5 years to develop at a cost of millions. Therefore solutions to the cryogenic needs for microsatellites are presented through research into the thermodynamic processes. Discussions will include efficiency improvements to reduce the size, weight, and power constraints of space qualified cryocoolers, as well as current state-of-the-art cryocoolers that meet the needs of military microsatellites.

INTRODUCTION

Space qualified cryocoolers have been extensively developed for large military and commercial satellite electro-optical (EO) infrared (IR) missions. These cryocoolers and the associated electronics routinely cost anywhere from $6-10M and can take 3-5 years to manufacture, making them a long-lead item for any EO IR space mission. Although progress has been made to reach a range of temperatures and heat loads, from 95 K at 10 W heat load to 10 K at 250 mW heat load, the input power required to operate is significant, sometimes up to 500 W. These space cryocoolers usually weight 22-25 kg, and if they are required to be located on a gimbal, this creates an even greater issue with the need for larger counterweights [1,2]. Clearly, the current state-of-the-art traditional cryocooler technology available for space far exceeds the limits of a microsatellite.

A trend has developed in recent years to invest in military satellites that are cheaper, more responsive and yet still perform the mission. This has increased the need for microsat technology mission enablers, such as cryocoolers. Unfortunately, due to the complex thermodynamic processes involved, cryocoolers do not scale down linearly. In fact, as the size is decreased, parasitic effects become more pronounced, increasing non-linearly [3]. This paper describes some of the research occurring at the Spacecraft Component Thermal Research Group, Air Force Research Laboratory (AFRL) in order to increase the efficiencies of space qualified cryocoolers to allow a reduction in size, weight, and power. This increase in efficiency will provide more options for an EO IR microsatellite, including better detector sensitivity and signal/noise ratio. Potential cryocoolers will also be discussed that can meet microsatellite needs, although these options are not always ideal, as will be shown.

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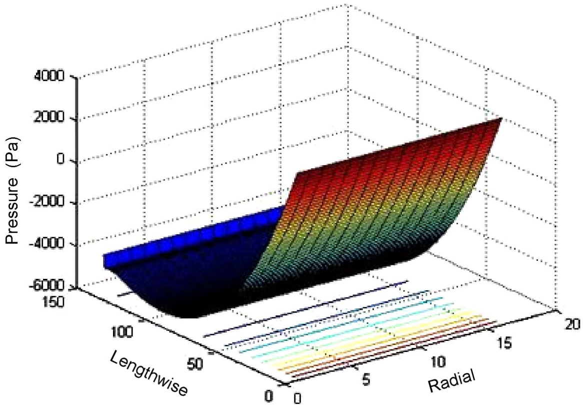

Figure 1. Pressure of He gas in inertance tube plotted against length and radius [5].

EFFICIENCY IMPROVEMENTS OF CRYOCOOLERS

Modeling and Simulation of Thermodynamics

At AFRL, two main modeling and simulation analyses are used: Computational Fluid Dynamics and Exergy Analysis. Computational Fluid Dynamics (CFD) for cryocoolers is numerical simulation of oscillating fluid flow at the component level. Often, pulse tubes are modeled with CFD, since the efficiency of pulse tube type cryocoolers is critically dependent on many details of its internal fluid flow [2]. CFD analysis allows for a delineation of the various loss mechanisms present in the cryocooler components. By understanding the loss mechanisms, the cryocooler can then be developed in the most efficient way possible, allowing a reduction in size, weight, and power, while maintaining the desired military requirements for an EO IR satellite [4]. This will open up many options to the microsatellite community. As an example, the Spacecraft Component Thermal Research Group at AFRL has modeled the inertance tube, which creates the phase shift for cryogenic cooling as shown in Figure 1. Understanding the pressure in the inertance tube (among other variables) improves the overall understanding of the fluid flow in the component. Improving component level efficiency increases the overall cryocooler efficiency [5].

Exergy analysis is a method used by the cryocooler community for the design and analysis of thermal systems. For pulse tube cryocoolers, it quantifies exergy flow and energy destruction at the component level, showing how the input exergy provided by the power input of the compressor is destroyed as the working fluid goes through its cyclic motion in the system. For instance, exergy analysis of the inertance tube has shown that the length of the tube significantly affects the efficiency of the pulse tube system [6].

Particle Image Velocimetry

Particle Image Velocimetry (PIV) validates CFD prediction modeling by studying internal fluid flow characteristics in pulse tubes to understand how the phase shift occurs. PIV at the Spacecraft Component Thermal Research Group is demonstrated by the measurement of velocity vectors in a seeded gas environment at cryogenic temperatures. Through understanding of the various flow mechanisms in the pulse tube, the cryocooler component can be developed more efficiency, thus increasing overall efficiency, and allowing for the reduction in size while maintaining the original cooling capacity. At AFRL, the experiment is in the early phase. Figure 2 shows the titanium dioxide in the pulse tube (seed material), using Nitrogen as the examined fluid [7]. In the next year, it is anticipated that PIV will validate the CFD modeling and simulations for loss mechanisms in cryocooler pulse tube components, allowing AFRL to generate design equations to remove the iterative manufacturing process plaguing cryocooler manufacturers, and allowing the development of smaller, more efficient space cryocoolers.

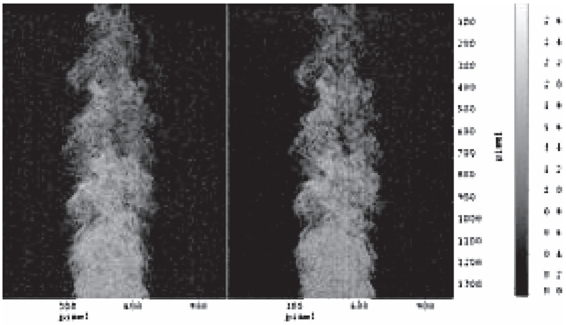

Figure 2. Adequate first fluid data with TiO_2 [7].

Solid State Cooling

There have been some recent advances in solid state cooling. A solid state cryocooler is ideal because it is small, extremely low weight, highly reliable, and has zero vibration. However, this is innovative technology research and development (R&D), and use of these devices for microsatellites, although ideal, will not be ready for flight for a few more years. Two particular types of solid state cooling to be touched briefly on include laser cooling and peltier cooling.

Laser cooling occurs in a crystal lattice by means of absorption of a photon, and then emission of a more energetic photon, with the extra energy extracted from lattice phonons. The removal of these phonons cools the crystal. Several studies have indicated that ytterbium or thulium doped solids can potentially provide efficient cooling below 100 K. A design for laser cooling is shown in Figure 3 [8].

Peltier cooling provides the same benefits as laser cooling, but through a different mechanism. Multistage thermoelectric coolers are stacked with superlattice materials, and the heat is rejected from one stage to the next as shown in Figure 4. Temperatures as low as 10 K are predicted [9].

MICROSATELLITE CRYOCOOLERS

There are a few options for microsatellite miniature cryocoolers today. Often, tactical (or ground-based) cryocoolers are chosen for missions because they are significantly cheaper than space qualified coolers. However, these tactical coolers have their own set of issues, including extensive vibration, and still do not provide the same level of cooling power as traditional space qualified cryocoolers, and therefore the capabilities of the microsat mission are reduced. Three notable

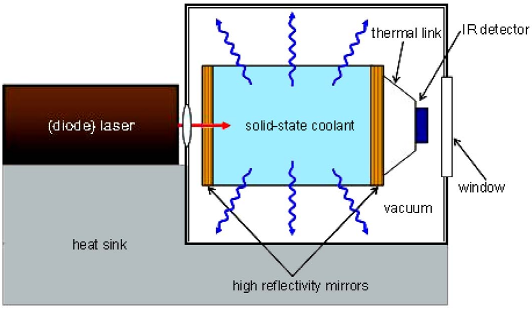

Figure 3. Laser cooling setup design [8].

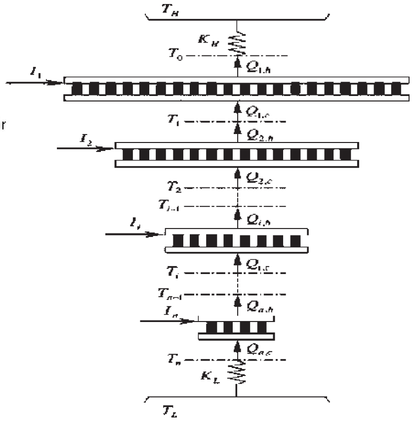

Figure 4. Scheme of n-stage TE cooler with finite thermal conductance heat exchangers [9].

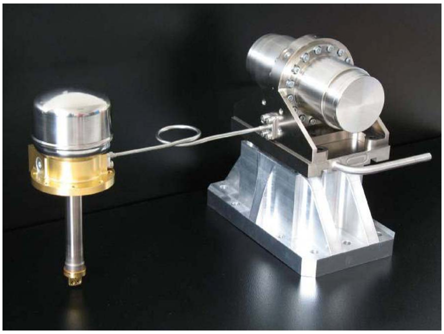

Figure 5. Air Liquide miniature cryocooler [10].

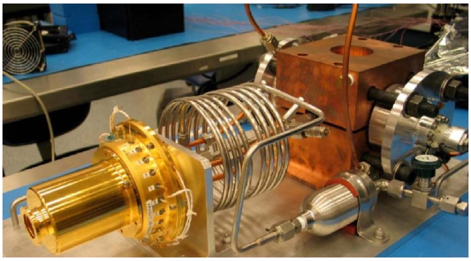

Figure 6. Raytheon Dual Use Cryocooler configured for bench top testing [12].

miniature space cryocoolers are discussed: the Air Liquide mini pulse tube, the Raytheon dual use cryocooler, and the Northrop Grumman high frequency microcooler.

Air Liquide has developed a small pulse tube cryocooler suitable for long life space applications. It is a single stage cooler that provides 1.5 W heat lift at 80 K for an input power of 35 W and a mass of 2.8 kg; its vibration level is 20 mN [10]. Figure 5 shows the advanced mini pulse tube developed for ESA's Sentinel-3 project; it provides 2.48 W heat lift at 80 K with 50 W input power [11]. This miniature pulse tube prototype is one example of a cryocooler suitable for microsatellites.

Raytheon has developed a dual use pulse tube cryocooler thermo mechanical unit (TMU) with a modified for space tactical cooler electronics intended for low cost and long life operations. Shown in Figure 6, the dual use cryocooler provides 1.5 W heat lift at 67 K, with 84 W input power and a mass estimated at 4.5 kg [12]. This miniature cryocooler prototype is also applicable to responsive space needs, as it can be assembled in just weeks versus months for the larger, traditional space qualified cryocoolers. It already has drive electronics to match the TMU [13].

Northrop Grumman Space Technology has developed a high frequency coaxial pulse tube microcooler optimized for rapid cool down. It provides 1.3 W of heat lift at 77 K, and 4.0 W of heat lift at 150 K, with input power of 35 W. Temperatures below 77 K can be achieved with reduced heat lift capacity. Shown in Figure 7, it weighs an impressive 0.86 kg. This cryocooler is compatible with both tactical and space qualified electronics, and is the lightest weight microcooler with 1.3 W heat lift [14].

These are excellent examples of some of the miniature cryocoolers that have the potential to meet microsatellite military needs. However, for microsatellites with masses less than 100 kg and a total payload power of less than 100 W, there is still a lot of research to be done to reduce input power, increase heat lift, and lower temperature in order to have the benefits of an on-board cryocooler outweigh the disadvantages.

Figure 7. NGST high frequency coaxial pulse tube microcooler [14].

SUMMARY

Although there are options for space miniature cryocoolers for use on an EO IR microsatellite, the quality of the data may be reduced due to cryocooler generated vibration as well as by limited heat lift capacity. Instead, the approach preferred at AFRL for miniaturizing cryocoolers is to increase the overall efficiency. By using R&D methods such as CFD, PIV, and innovative pursuits in vibration reduction and solid state cooling, the potential to decrease size, weight and power is significant. Ultimately, research into efficiency will lead to cryocoolers for microsatellite military applications becoming available for any EO IR mission requirements, thus enabling the desire for cheaper, more responsive, smaller microsats.

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