Vibration-Free, Hybrid Cryocooler for 4 K Space Applications

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ABSTRACT

Future astronomical observatories and surveillance satellites utilizing infrared, far infrared, and submillimeter detectors will require long-life mechanical cryocoolers that provide cooling at temperatures down to 4 K. These missions share a common set of core requirements. The thermal efficiency of current space cryocoolers for 4 K operation is inadequate, and laboratory cryocoolers that provide cooling at 4 K are inefficient and lack a clear development path towards flight. This paper describes a hybrid cryocooler that is lightweight, compact, reliable, efficient and suitable for space missions. The cryocooler consists of centrifugal compressors at the warm end that provide continuous flow to a reverse-Brayton upper temperature stage and a Joule-Thomson (J-T) lower temperature stage. The Brayton stage is expected to operate at nominally 15 K, and the J-T stage is expected to operate at 3-5 K. The Brayton and J-T cycles are both continuous flow cycles, allowing significant separation distances between the warm and cold components. The cryocooler produces negligible vibration and can uniformly cool remote and distributed loads with extremely small temperature differences and performance penalties. In addition, the components utilized in the cryocooler are relatively mature with a high Technology Readiness Level (TRL).

INTRODUCTION

Creare Incorporated has been developing miniature gas bearing turbomachines and compact heat exchangers for cryocoolers and cryogenic systems for over 30 years. The cryocoolers are based on the reverse-Brayton cycle and have been developed for aircraft and space applications where high reliability and low mass are critical parameters. The components have been developed for inclusion in our cryocoolers as well as for cryogenic systems used in the Department of Energy's national laboratories. We have demonstrated components at temperatures as low as 4.2 K and closed-loop cryocoolers at temperatures down to 11 K. The most widely known cryocooler produced by Creare is the NICMOS Cryocooler which operated for more than 6.5 years on the Hubble Space Telescope before a problem with the cooling loop that interfaces with the NICMOS dewar caused the system to be deactivated.[1] The plan to restart of the NICMOS Cryocooler is in process. The NICMOS Cryocooler provides 7 W of refrigeration at 70 K.

The reverse-Brayton cycle scales very well to low temperatures due to favorable thermodynamics. The efficiency of the cycle improves with increasing temperature ratio between the warm and cold end, and, in fact, more closely approximates the Carnot cycle at low temperatures and low pressure ratios. That said, the extension of turbo-Brayton cryocoolers to temperatures of 10 K and

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below requires overcoming several technical obstacles associated with the primary mechanical components. These obstacles and our approaches to overcoming these obstacles are described below.

- Centrifugal Compressors. The need to utilize helium as the cycle gas limits the maximum pressure ratio that can be attained with a single-stage centrifugal compressor. This low pressure ratio leads to a system with high flow rates and large recuperators. This obstacle is readily addressed by connecting several compressors in series. We have demonstrated the operation and performance of up to three compressors connected in series, which is adequate for most applications. These compressors have been demonstrated at power levels down to 50 W in helium with high efficiency.
- Recuperative Heat Exchangers (Recuperators). The large temperature difference between the warm and cold end of the cryocooler at low temperatures increases the recuperation requirements, leading to large cryocoolers that are often not suitable for space applications. Creare has developed and demonstrated an advanced recuperator technology that dramatically reduces the size and mass of low temperature recuperators. The advanced recuperator utilizes silicon slotted plates for the heat transfer elements. Silicon has extremely high conductivity at temperatures below 100 K and is lightweight. This advanced recuperator has successfully completed thermal vacuum, temperature cycling and vibration testing.[2] The recuperation from the heat rejection temperature to 100 K is still quite challenging due to the low flow rates associated with these low capacity systems. Several options exist to reduce the size and mass of the warm recuperator. These options include advanced recuperator technology such as the silicon-based recuperator or precooling. The precooling can take the form of passive precooling using cryogenic radiators or active precooling using a Stirling-class cryocooler. The optimum approach for a given application depends on the results of payload-level trades.
- Expansion Turbines. The low refrigeration requirements at temperatures less than 10 K for most space systems and some terrestrial systems correspond to extremely low power levels for the expansion turbines. At low power levels, the physical features of the turbine must be extremely small and the manufacturing tolerances must be appropriately reduced in order to maintain high efficiency of the expansion process. We have demonstrated good efficiency at power levels down to about 500 mW and are currently developing higher efficiency turbines at this power level. Many future applications will require less than 500 mW of refrigeration which will likely require a new paradigm in miniaturization and fabrication technology to attain high efficiency.

Our approaches for the compressors and recuperators for low-temperature cryocoolers are well developed and mature for space applications. The expansion turbine technology is mature for refrigeration powers nominally greater than 500 mW, but would require significant development at lower values. To further assess the appropriate technology for low-capacity, low-temperature space applications, Creare initiated an internally funded project to design a cryocooler. The optimum cryocooler was determined to be a hybrid Brayton-J-T cycle. The results of this design study are described in this paper.

HYBRID CRYOCOOLER CONCEPT

A schematic of the cryocooler cycle is shown in Figure 1. The cryocooler is a hybrid cycle, consisting of three centrifugal compressors that provide continuous flow to a reverse-Brayton upper temperature stage and a J-T lower temperature stage. The Brayton stage is expected to operate nominally at 15 K, and the J-T stage is expected to operate at 3-5 K. The cycle gas is Helium-3, Helium-4 or a mixture depending on the cooling temperature requirement. The Brayton and J-T cycles are both continuous flow cycles, allowing significant separation distances between the warm and cold components. The cryocooler can be configured with or without precooling. The precooling can be passive or active depending on the thermal design of the payload. In Figure 1, the hybrid cryocooler is shown with a two-stage Stirling-class cryocooler (standard or pulse-tube variant), which precools the hybrid cryocooler at two temperatures. The precooling serves two purposes:

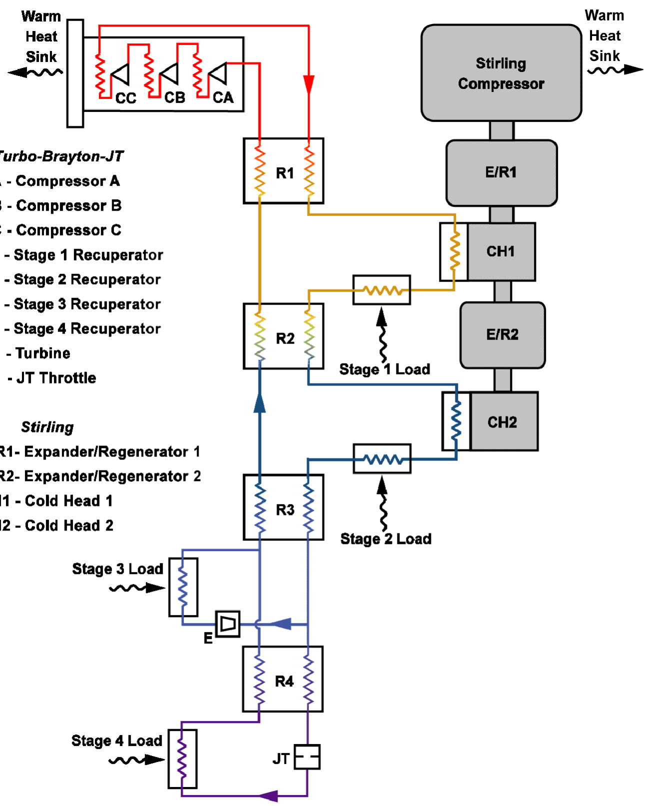


Figure 1. Cycle schematic for hybrid Brayton-J-T cryocooler with pre-cooling.

(1) it reduces the recuperation requirements for the hybrid cycle, thereby reducing the overall size of cryogenic components; and (2) it allows the hybrid cooler to provide remote and distributed cooling at two higher temperatures to intercept parasitics. The minimum temperature for precooling is likely greater than 30 K due to the poor area scaling of passive radiators at low temperatures and the drop in efficiency of Stirling-class cryocoolers at low temperatures.

To illustrate the size, mass, and performance benefits of the hybrid cryocooler, we assessed the cooling system shown in Figure 1 to the requirements given in Table 1. These requirements are based on the conceptual design of the thermal management system for NASA's SAFIR Mission.[3] The hybrid cryocooler, including the Stirling precooler, requires only 600 W of DC input power to simultaneously provide 230 mW of refrigeration at 4.0 K and an additional 1.0 W of refrigeration at each upper stage load (15 K, 40 K, and 100 K) for shielding and sunshade cooling. The 4 K load includes a 50% margin relative to the requirement due to the preliminary and uncertain nature of the thermal loads. The Stirling precooler provides 5.1 W/1.0 W of gross/net refrigeration at 100 K and 2.8 W/1.0 W at 40 K. The difference between the gross and net refrigeration is used to reduce the recuperation requirements of the hybrid cryocooler. The AC input power into the Stirling compressor is 200 W. This is based on the assumption that its coefficient of performance (COP) is 14% of the Carnot cycle, an achievable figure for these loads and temperatures. The AC input power to the centrifugal compressors is approximately 120 W per compressor. To compare the hybrid cycle performance to other cryocoolers demonstrated or under development, we determined the specific power of the cryocooler with all refrigeration loads normalized to the 4 K stage using Carnot scaling. The specific power of the hybrid cryocooler with precooling is less than 1000 W/W, corresponding to a COP of 7.4% of a Carnot cycle, This performance is far better than any 4 K cryocooler existing or under development, as shown in Figure 2. In addition, the temperature rise across each

Table 1. Cryocooler performance predictions.

Parameter	Target	Prediction
Warm End		
Heat Rejection Temperature	300 K	300 K
AC Input Power to Brayton-JT Compressors	Minimal	350 W
AC Input Power to Stirling Compressor	Minimal	200 W
Total Bus DC Input Power	Minimal	600 W
Stage 1		
Net Refrigeration	Not Specified	1.0 W
Pre-Cooling	Not Applicable	5.1 W
Temperature	100 K	100 K
Temperature Rise Across Load Interface	Minimal	0.25 K
Stage 2		
Net Refrigeration	Not Specified	1.0 W
Pre-Cooling	Not Applicable	2.8 W
Temperature	40 K	40 K
Temperature Rise Across Load Interface	Minimal	0.24 K
Stage 3		
Net Refrigeration	1.0 W	1.0 W
Pre-Cooling	Not Applicable	0.0 W
Temperature	15 K	15 K
Temperature Rise Across Load Interface	Minimal	0.45 K
Stage 4		
Net Refrigeration	0.15 W	0.23 W
Pre-Cooling	Not Applicable	0.0 W
Load Temperature	4.0 K	4.0 K
Temperature Rise Across Load Interface	Minimal	0.07 K

load is extremely small due to the high conductance of the circulating gas. This feature will permit a high degree of temperature uniformity when cooling remote and distributed loads.

The high thermodynamic performance can be attributed to the high efficiency of the centrifugal compressors and expansion turbine, the high thermal effectiveness of the recuperators, and the selection of the optimum cycle operating conditions. He-3 has a significant J-T effect at the modest

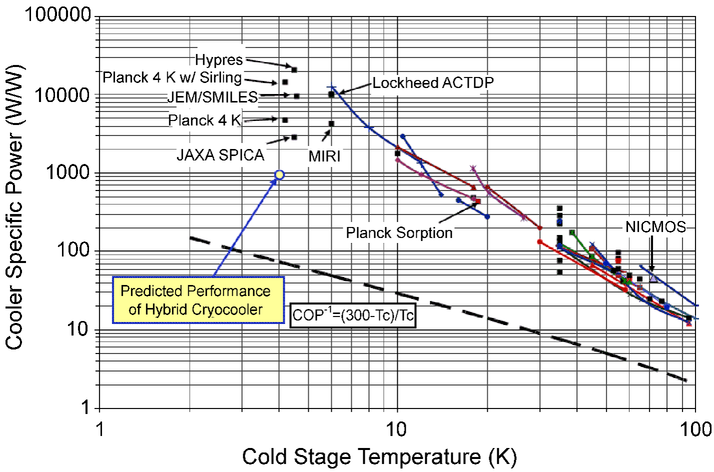


Figure 2. Performance of cryocoolers existing or under development

pressures and pressure ratios consistent with those used in turbo-Brayton cryocoolers, which allows the turbomachines to operate at peak efficiency. A turbine is not utilized for the fourth stage expansion because a J-T throttle is simpler, more scalable, and more efficient at low cooling capacities. In fact, the J-T expansion at the operating conditions selected corresponds to an isentropic efficiency of 56%, an extremely high value for such a low capacity expansion. The J-T effect is also significant at 15 K, which will simplify cool-down. During cool-down, the turbine will cool the fourth stage to nominally 15 K, at which point the J-T effect will be large enough to quickly cool the stage to its operating temperature of 4 K.

The Brayton-J-T hybrid cryocooler would likely be configured in three primary modules: a warm module, intermediate module, and cold module. The intermediate module would only be used if a precooler was included in the cryocooler. A description of each module follows.

Warm Module

The warm module consists of the three compressors with integral aftercooler, Stage 1 recuperator and electronics, and is shown in Figure 3. The warm module rejects all heat produced by the cryocooler through a single mechanical and thermal interface. It would likely be located near the spacecraft heat rejection system remote from the objects to be cooled, and would be connected to the intermediate module through tubing and wire harnesses. The estimated mass of the warm module is 16 kg.

Intermediate Module

The intermediate module consists of the Stage 2 recuperator and Stage 1 and 2 interface heat exchangers. It would be thermally and mechanically mounted to the precooler, and connected to the warm and cold modules of the hybrid cryocooler through tubing and wire harnesses. The estimated mass of the intermediate module is 3 kg.

Cold Module

The cold module consists of the turbo-alternator and J-T throttle, and Stage 3 and 4 recuperators and interface heat exchangers. It is shown in Figure 4. The cold module provides the refrigeration

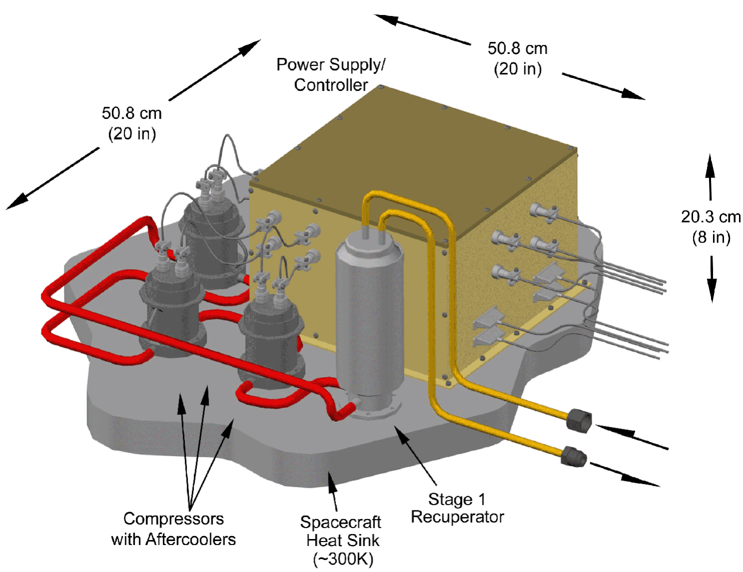


Figure 3. Warm module of Brayton-J-T hybrid cryocooler

to the third and fourth stage, and is connected to the intermediate module through tubing and wire harnesses. It is located near the object to be cooled and uses a single mechanical interface at the base of the Stage 3 recuperator for integration with the payload. The cold module brackets and mounting interface are manufactured from low conductivity materials to minimize conductive parasitics. The mass of the cold module is estimated to be 4 kg.

The overall mass of the hybrid cooler with electronics is 23 kg. The estimated mass of a two-stage Stirling cryocooler with electronics is 21 kg. Therefore, the total cooling system mass is 44 kg with all but 5 kg located remote from the objects to be cooled.

COMPONENT MATURITY

The hybrid cryocooler components are quite mature with the lowest TRL at 5. In addition, there are several cryocooler options from different vendors for the Stirling-class precooler in a standard or pulse-tube configuration with a TRL of 5 or greater. The key cryocooler components for the Brayton-J-T hybrid are briefly described in the following paragraphs.

Hybrid Cryocooler Electronics

The electronics provide AC power to drive the compressors, control the speeds of the turbomachines, and control the refrigeration load temperatures. The compressor power electronics utilize the Rotating Field Inverter design that Creare developed specifically for efficient operation of high-speed turbomachines (U.S. Patent 6,023,420). Creare recently developed a version of these electronics for space, which is radiation hardened to greater than 300 kRad, has low EMI/EMC, can withstand launch loads, is conductively cooled through a contact interface, and uses hybrid micro-circuits to minimize size and mass. The packaging approach is also extremely modular allowing weight and performance optimization for power levels from 5 W to 500 W by changing the power transformer board. All control and switching logic is suitable for power levels up to at least 500 W. The compressor inverter was tested to a radiation level of 1 MRad.

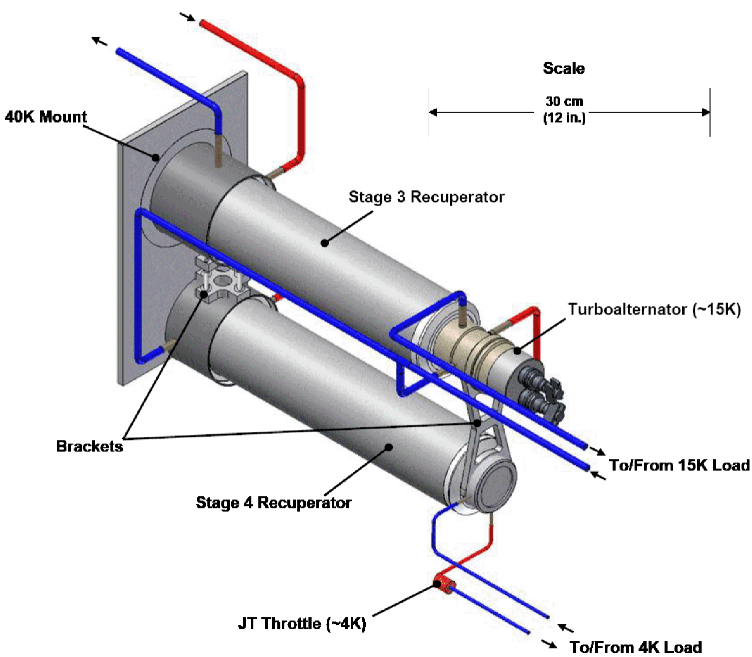


Figure 4. Cold module of Brayton-J-T hybrid cryocooler.

Compressors/Aftercoolers

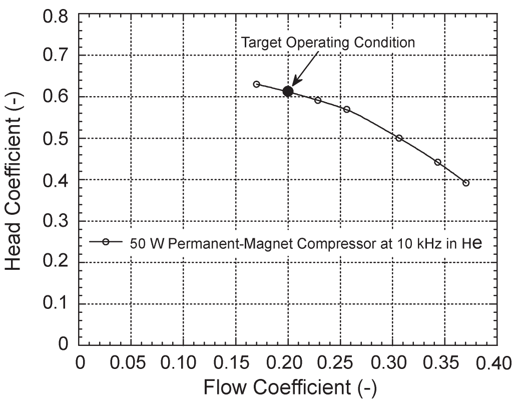
Each compressor/aftercooler pair is a single assembly and utilizes identical designs except for the rotors which have been tailored based on inlet pressure.. The assemblies would be mounted to the spacecraft heat rejection system. The compressors provide the pressure ratio and circulate the cycle gas, while the aftercoolers remove the heat of compression from the cycle gas. The compressors were developed on a prior NASA program and demonstrated to a TRL of 5.[4] They use non-contacting gas bearings for long-life, maintenance-free operation. Their design is based on the compressor in the NICMOS[1] cryocooler. A photograph of an Engineering Model (EM) level compressor and data from performance tests in Helium-4 are shown in Figure 5.

Recuperators

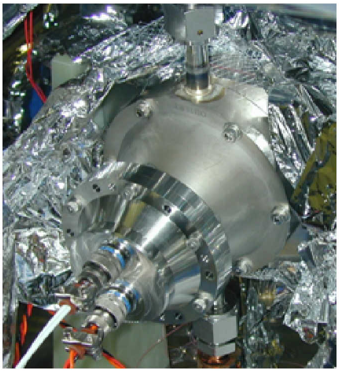
The four recuperators cool the high pressure stream using the low pressure stream returning from the turbo-alternator and J-T throttle. This form of "internal precooling" improves the thermodynamic performance of the hybrid cycle. The recuperators utilize Creare's silicon slotted plate technology, which has been demonstrated to a TRL of 5.[2] These recuperators are extremely light and compact. Each recuperator includes a stack of silicon plates; each of which has been etched to create thousands of micro flow passage. The headers and shells are fabricated from a titanium alloy for low mass and low conductivity. Prior programs have demonstrated the thermal performance of this technology and its ability to endure thermal cycles and simulated launch vibration. A photograph of the prototype unit during vibration testing is shown in Figure 6.

Turboalternator

The turboalternator produces refrigeration at Stage 3 and cools Stage 4 to a temperature below the J-T inversion temperature for He-3. It produces refrigeration by converting aerodynamic work performed in the turbine rotor into electrical power using a permanent-magnet alternator. For this cryocooler, the electrical power produced by the alternator is nominally 2 W. The power is typically fed up to the warm end of the cryocooler through electrical harnesses where it is dissipated or recovered. Alternatively, for some applications this power can be used to power cryogenic electronics. The turboalternator is a variant of the NICMOS turboalternator optimized for lower cooling capacities and operating temperatures. The primary physical difference between the two designs is that the aerodynamic features in the rotor and nozzle ring are optimized for the respective flow conditions. Brassboard and EM versions of the lower capacity turboalternator have been tested at temperatures down to 12 K and power levels down to 1 W. The turboalternator technology is currently at a TRL of 5.



a. Performance test in Helium-4



b. During integration

Figure 5. Engineering model compressor.

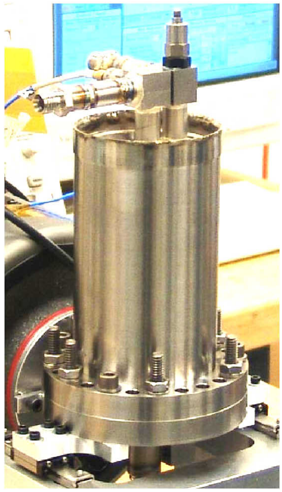


Figure 6. Silicon recuperator prototype during vibration testing.

The remaining components of the hybrid cryocooler are quite mature and have low development risk. These components include insulation, brackets, thermal shields, tubing, harnesses, a J-T throttle, and thermal interface heat exchangers. An estimate for the mass of these components was included in the overall mass estimate.

HYBRID CRYOCOOLER FEATURES

The cryocooler sizing example described in this paper illustrates the performance and mass benefits of the technology for a specific set of cooling requirements. As compared to an exclusive J-T cryocooler, the hybrid cryocooler should provide higher reliability, reduce operational complexity, lower input power, and increase conductance between the objects to be cooled and cryocooler. As compared to a multistage Stirling-class cryocooler for 4 K cooling, the hybrid cryocooler should have much higher thermodynamic efficiency. In addition to the performance and mass benefits, the hybrid cryocooler has the following favorable features.

High Reliability

The only moving parts in the hybrid cryocooler are the miniature rotors in the turbomachines. Unlike most J-T cryocoolers, the hybrid cryocooler does not require valves to rectify the AC flow from reciprocating compressors nor does it utilize rotary vane or scroll compressors, which have wearing parts. The rotors in the hybrid cryocooler are supported on gas bearings. During operation, there is no mechanical contact between the bearings and rotor. Mechanical contact does occur during start-up and coast-down when surface speeds are low. Low friction coatings are applied to both the shaft and bearings to minimize wear during these events. Several tests have been performed on turbo-Brayton components to demonstrate their reliability and endurance.[5,6] In addition, the hybrid cryocooler has an all metal, hermetic pressure boundary and the contamination control methods have been demonstrated for long-life operation. The result is that the hybrid cryocooler should meet all space requirements for life and reliability.

Improved Cooldown

The thermodynamics in the Brayton stage relies on near isentropic expansion to produce cooling as opposed to the isenthalpic expansion of a J-T cryocooler. The expansion process in the Brayton stage produces cooling at all temperatures whether the cycle gas behaves as an ideal or real gas. The isenthalpic expansion only produces cooling at low temperatures so cooldown is an issue with most J-T cryocoolers. This issue is typically addressed by using a separate cryocooler to precool the cold end of the J-T system. Since the J-T orifice is quite restrictive at high temperatures, a cryogenic valve is sometimes placed in parallel with the orifice to produce a bypass during cooldown. The hybrid cryocooler gets around these issues by using the Brayton stage for cooldown of the cold end. Once at 15 K, the J-T throttle is producing significant refrigeration due to the large J-T coefficient and the modest flow resistance. The heat capacity of the materials is also low at this temperature, allowing a quick cooldown. The result is reduced operational complexity and increased reliability for the hybrid cryocooler.

High Conductance Cryogenic Heat Transport

J-T cryocoolers typically operate at high pressure ratios and low mass flow rates—the mass flow rates are typically one order of magnitude less than turbo-Brayton cryocoolers for the same cooling requirements. The lower flow rates decrease the recuperation requirements, but produce larger temperature difference between the objects to be cooled and the cryocooler. The result is increased input power and an inability to uniformly cool remote or distributed objects. The Brayton-J-T hybrid cryocooler uses lower pressure ratios and higher flow rates than conventional J-T cycles to decrease the temperature differences. As shown in Table 1, the temperature rises between the inlet and outlet of each load is extremely small. This eliminates the need for a two-phase cryogenic heat transport and load management system.

Highly Flexible Spacecraft and Payload Integration

The hybrid cryocooler is a continuous flow system with a component-based topology that permits flexible integration with thermal interfaces of the payload(s) and spacecraft. Heat may be transported from the active elements of the cryocooler to radiator surfaces or from the objects being cooled by a steady flow of gas through flexible or rigid lengths of tubing. Similarly, multiple objects at separate locations can be cooled using a steady flow of gas through flexible tubes.

Vibration-Free Operation

The miniature, low-mass rotors used in the turbomachines are the only moving parts in the hybrid cycle. They are precision-balanced for high-speed operation. Inertial loads from the shafts are negligible, and the gas bearings provide damping. The Stage 1 and 2 loads are effectively isolated from vibrations produced by the Stirling-class cryocooler using flexible tubes leading to the load interfaces. This eliminates the need for complicated vibration control.

CONCLUSIONS

This paper describes the design of a hybrid cryocooler suitable for future astronomical observatories and surveillance satellites. The cryocooler consists of three centrifugal compressors that provide continuous flow to a reverse-Brayton upper temperature stage and a J-T lower temperature stage. The Brayton stage is expected to operate at nominally 15 K, and the J-T stage is expected to operate at 3-5 K. The specific power of the proposed cryocooler is better than any 4-6 K cryocooler existing or under development. The Brayton and J-T cycles are both continuous flow cycles, allowing significant separation distances between the warm and cold components which will simplify integration. The only moving parts are the rotors in the miniature gas-bearing turbomachines that compress or expand the working fluid. The use of a single-phase working fluid and gas-bearing turbomachines results in a cryocooler that produces no detectable vibration. The primary cryocooler components are all at a TRL of 5 or above with heritage to TRL 9 technology. The performance modeling is mature and based on component-level experimental data.

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