DEVELOPMENT OF A NOVEL BRAYTON-CYCLE CRYOCOOLER AND KEY COMPONENT TECHNOLOGIES

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ABSTRACT

Brayton-cycle cryocoolers are being developed to provide efficient cooling in the 6 K to 70 K temperature range. The cryocoolers are being developed for use in space and in terrestrial applications where combinations of long lifetime, high efficiency, compactness, low mass, low vibration, flexible interfacing, load variability, and reliability are essential. The key enabling technologies for these systems are a mesoscale expander and an advanced oil-free scroll compressor. Both these components are nearing completion of their prototype development phase. The emphasis on the component and system development has been on invoking fabrication processes and techniques that can be evolved to further reduction in scale tending toward cryocooler miniaturization.

INTRODUCTION

The Brayton-cycle was developed in the nineteenth century by George Brayton, a pioneer in the development of internal combustion engines and the continuous ignition combustion (turbine) engine. There are many forms of the Brayton-cycle, ranging from the simple open cycle used in gas turbine and jet engines to the closed cycle with external combustion; the reverse Brayton-cycle is used to provide cooling, having the potential for excellent thermodynamic efficiency. Development of reverse Brayton-cycle technology for cryogenic cooling in space has been previously funded by both the Air Force Research Laboratory (AFRL) and NASA [1, 2].

The Brayton-cycle cryocooler is a recuperative system that derives its thermodynamic performance from efficient compression, expansion, and heat exchange processes. The key components in a system include the compressor, expander, counterflow heat exchangers, and a cold-end heat exchanger. TAI has been developing a Brayton-cycle cryocooler design that incorporates new enabling technology including a DC-flow oil-free scroll compressor, a reciprocating mesoscale expander, and compact high-effectiveness counterflow heat exchangers. FIGURE 1 shows a component arrangement for a cryocooler of this type. An intermediate stage (precooler) is used in lower temperature cooling applications to

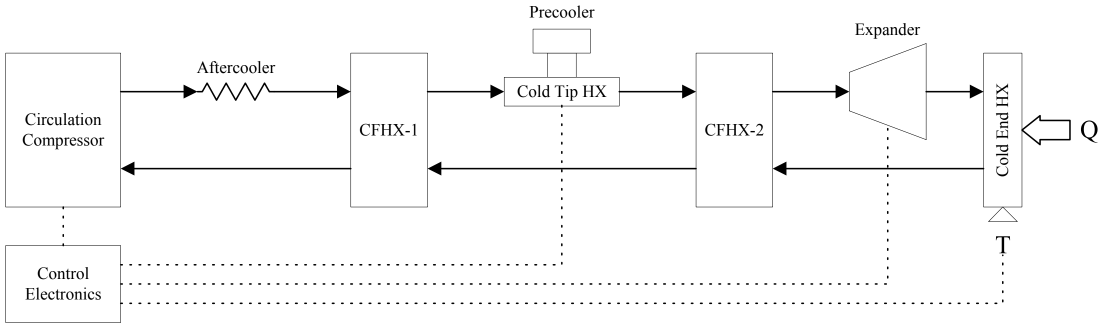


FIGURE 1. Component arrangement for a Brayton-cycle cryocooler

compensate for imperfect heat transfer in the warm recuperative heat exchanger and to intercept parasitic heat load into the cold end. This stage can be a separate system, such as a Stirling or pulse tube cryocooler, or ultimately another expander that is integral with the fluid system. Second stage cooling at an intermediate load temperature may also be provided with proper component sizing.

FEATURES AND APPLICATIONS

Of the cryocoolers that have been developed for long-life space application (e.g.; Brayton, Stirling, pulse tube, Joule-Thomson, and sorption), each has its own unique set of integration and operational characteristics. Heat lift, load temperature, power input, physical size, and mass are all interrelated. To choose the proper cryocooler, one must consider very carefully the requirements of the package to be cooled and understand the system-level thermal and mechanical environments.

The Brayton-cycle cryocooler has many attractive features that can benefit actively cooled systems. Its modular configuration allows system operation flexibility; e.g., changes can be made during integration with the sensor package since components can be independently integrated. A more complete list of its features and benefits is summarized in TABLE 1. TAI's Brayton-cycle cryocooler offers capability not available by other cryocooler types in several areas that are described below.

TABLE 1. Features and benefits of TAI's Brayton-cycle cryocooler

Features	Benefits
Long life	- Expander has no wearing parts and moving parts have been designed so stresses are well below fatigue limits. - System is not resonant and therefore can undergo accelerated life testing and statistically significant failure analysis.
Minimum vibration	- Mass of the moving parts is very small, frequency is not excessive. - Piston assemblies can be arranged back-to-back, compensating momentum effects.
Low cost	- Modular design of the expander and use of integrated circuit processes to fabricate it make automated assembly possible. - All of the technology to support the expander is simple, inexpensive, and often commercially available.
Compact and lightweight	- High efficiency of expander and heat exchangers greatly reduces weight and size of the package.
Simplified integration	- Remote/distributed cooling means no electronics in vicinity of load and all mechanical vibrations are remote from load. - Concerns about mechanical integrity of cooler at the interface are eliminated. - Electronics and compressor can be conveniently located, as design dictates.

Distributed Cooling

An example is provided to illustrate advantages of modularity and distributed cooling available with TAI's mesoscale version of the Brayton-cycle cryocooler. Consider simultaneous cooling of six high temperature superconducting filters/amplifiers behind antennas located on wing tips and along the bottom of a large aircraft; refer to FIGURE 2. In this example, the compressor is located in the cabin area of the aircraft with a cold assembly located at each filter. Small diameter fluid lines routed from a central manifold connect each cold assembly to the compressor.

The flow impedance impact on compressor power was assessed for such remote cooling applications. The pressure drop in a 50-ft long, ¼-in diameter line is less than 1 psi at typical operating conditions. To compensate for this pressure loss without impacting heat lift capacity would require just a few watts of additional compressor input power. The Brayton-cycle cryocooler combines the attributes of DC-flow and an efficient expansion process to provide effective and efficient cooling of multiple filters located at large distances from the compressor to isolate potential electromagnetic and vibration interferences.

Large Loads at Low Temperature

There is interest by DOD and NASA in solar thermal propulsion systems to power Orbit Transfer Vehicles. This propulsion technology is capable of offering 2-10 times the efficiency of existing chemical propulsion systems while simultaneously providing 30-100 kW of electrical power at one-third to one-tenth the cost of advanced photovoltaic systems. In order to accomplish these missions, bulk cryogenic hydrogen storage in space is needed for periods up to five years. Active cryocooler systems are needed that can cool tens of watts at 25-30 K to enable long-term liquid hydrogen (LH_2) storage in space. The TAI Brayton-cycle cryocooler can be configured to provide this large-load capability in the required temperature range.

Small Applications

The components for the TAI Brayton-cycle cryocooler have the potential for being significantly reduced in size. Detailed system design and analysis have been completed to show a dramatic size reduction over the demonstration cryocoolers currently being developed. FIGURE 3 shows the TAI mesoscale cryocooler for cooling 1 W at 70 K. The outside dimensions are 3.3-in OD x 5.8-in length. With additional development, the cryocooler can be reduced to even smaller sizes.

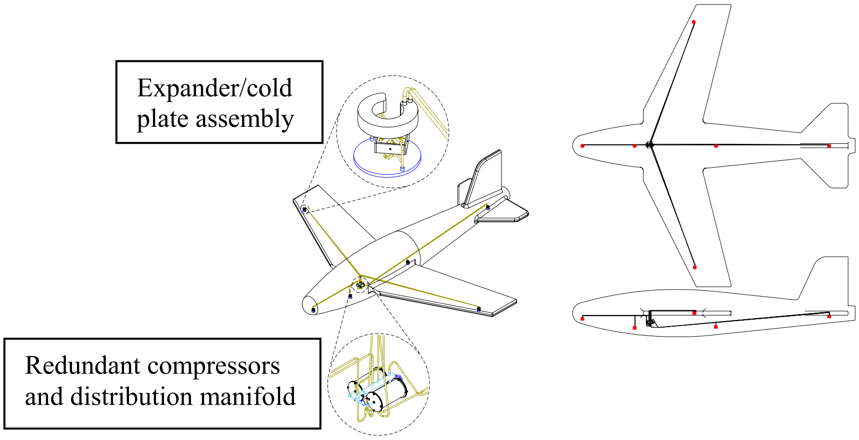


FIGURE 2. Aircraft filter cooling application

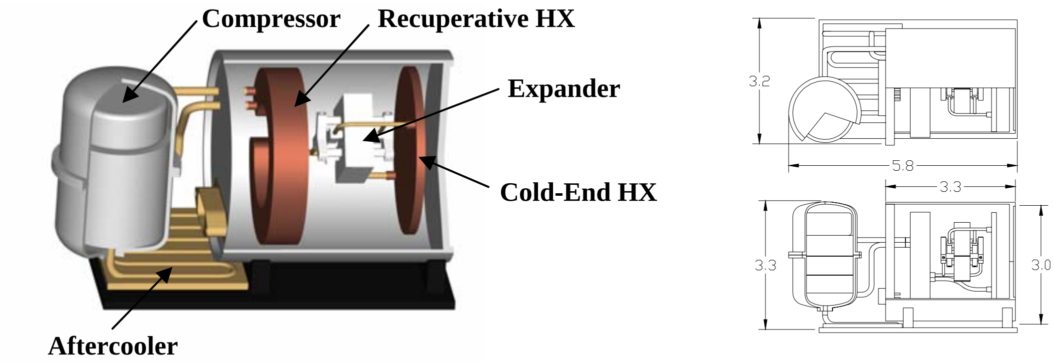


Figure 3. Small Brayton-cycle cryocooler for cooling at 70 K

SYSTEM APPROACH

In addition to 70 K cooling, we are developing cryocoolers for 35 K, 10 K, and 6 K cooling applications. The component arrangement for each of the cryocoolers is similar, but lower temperature applications require the use of an intermediate cooled stage and an additional recuperative heat exchanger to achieve desired cooling capacities. The development approach has been stepwise with the initial focus on component prototyping. Demonstration of the reliability and efficiency of the key system components is planned prior to full system integration. The key to enabling this Brayton-cycle cryocooler approach is miniaturization of the expander through micro-electro-mechanical systems (MEMS) technology. A prototype expander is currently being fabricated and will be tested in an open-loop circulation system to characterize its cooling capacity and operational modes. Expander control electronics incorporating a unique circuit topology for rapidly switching the relatively high voltages required to operate the device have been designed and circuit board fabrication is nearly complete. A breadboard system is planned to further demonstrate expander operation in a closed-loop configuration. Exclusive of the expander, this system will be assembled using mostly commercial components. An advanced prototype system has been designed; it incorporates the unique scroll compressor, a compact high effectiveness heat exchanger, and system-level control electronics. This system is designed to demonstrate the long-life performance that is required for both space and terrestrial applications. FIGURE 4 shows this cryocooler that has been designed to provide cooling at 6 K.

Analytical models have been developed to guide the design process and predict cryocooler performance relative to component efficiencies. Parametric analyses have been useful in identifying the system sensitivities and operational limitations that exist due to component performance uncertainties. TABLE 2 shows results from these studies in terms of cooling capacity sensitivity to key component performance values over conservative ranges. The figure of merit expressed is the percent loss of available cooling for each

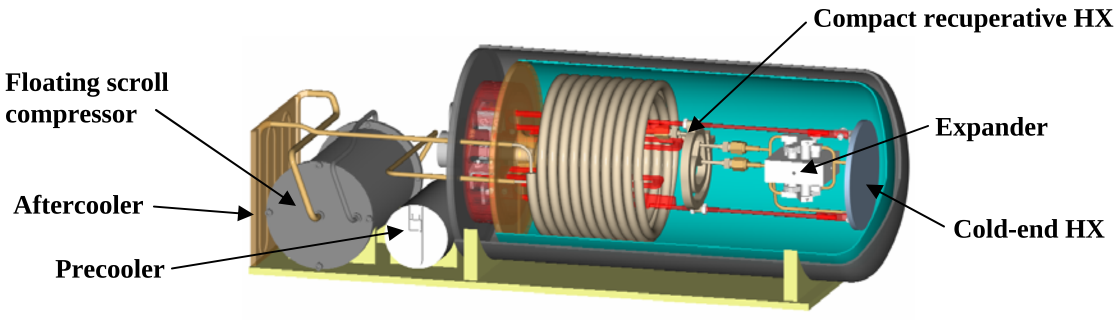


FIGURE 4. Advanced prototype Brayton-cycle cryocooler for 6 K cooling

TABLE 2. System sensitivity in terms of percent heat lift loss per percent change in component performance

PARAMETER	SENSITIVITY %/%	RANGE
Compressor Isentropic Efficiency	1.3	$0.4 < \eta < 0.6$
Expander Isentropic Efficiency	2.5	$0.6 < \eta < 0.8$
CFHX-1 Effectiveness	11	$0.94 < \varepsilon < 0.98$
CFHX-2 Effectiveness	24	$0.94 < \varepsilon < 0.98$

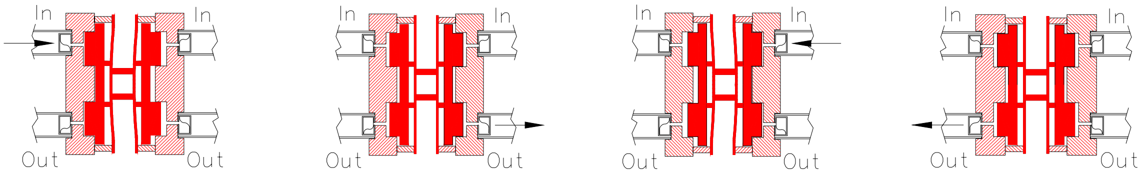
percent reduction in component efficiency at constant input power. The value in such a study is identifying and focusing component developments in areas that have the most profound impact on system performance.

COMPONENT DEVELOPMENTS

Expander

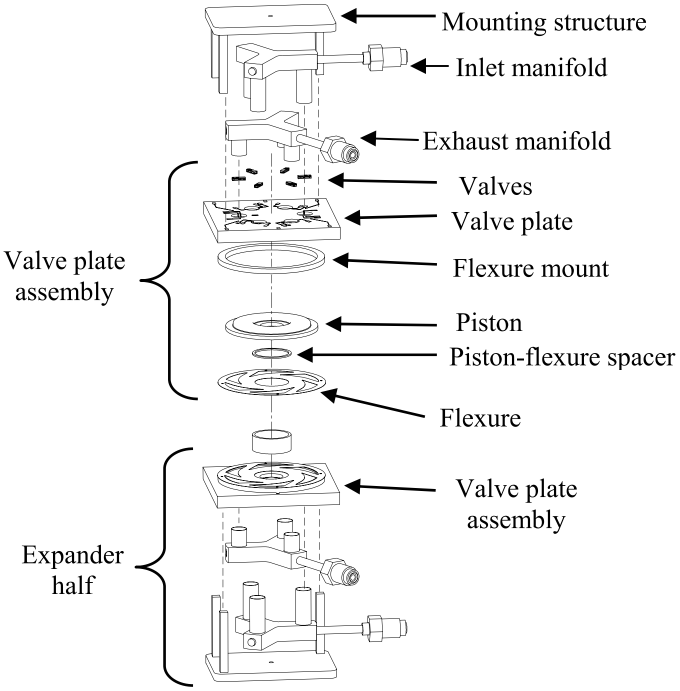
The expander assembly is the key cooling system component, enabling the actualization of a cryocooler with high efficiency, compact size, and low mass. TAI has been developing a mesoscale expander that operates based upon electrostatic force. In effect, the expander is a transducer that operates by creating an electrostatic force between two electrodes in a precision capacitor and allowing pressurized gas to separate the electrodes. Since work is the product of force and distance, the gas does work against the electrostatic force by separating the electrodes. This work is eventually dissipated as Joule heating in a warm load resistor. By doing work and removing it from the system, the expansion process can be carried out at nearly isentropic state and the dissipated energy provides an efficient means to reduce the gas temperature. The expander is configured in an opposing piston arrangement and as gas is expanded on one side, the already cooled gas is expelled on the opposite side. FIGURE 5 illustrates the expander operation. In FIGURE 5(a) one side of the expander is being filled by opening a series of valves to the high pressure side of the system; in FIGURE 5(b) the gas is expanded in the left side while the previously expanded and cooled gas on the right side is expelled to the low pressure side of the system. In FIGURES 5(c) and 5(d) the process is repeated from the opposite side.

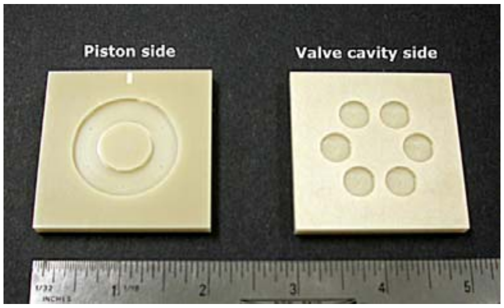
The stroke of the expander piston is limited to less than 100 μm while the gap between the capacitor electrodes increases from an initial separation of just a few μm when the electrodes are charged. The expansion volume is kept small to limit the operating voltage across the capacitor; however, the device is designed to operate at up to 100 Hz to provide volumetric throughput necessary for typical cooling capacity requirements. Flow into and out of the expansion volume is managed through an array of miniature valves that also use electrostatic force to actuate. The capacitor structures for both the piston and valve operations are formed using typical semiconductor processes that include physical vapor deposition (PVD), chemical mechanical polishing (CMP), photolithography, etching, and laser ablation. FIGURE 6 shows the expander assembly and its primary components.



(a) (b) (c) (d)

FIGURE 5. Expander operation sequence





Ceramic valve plates

Expander assembly

FIGURE 6. Expander components and assembly

Ceramic is used as the primary material in the valve plate, piston, and valve components. Careful attention has been given to matching the coefficient of thermal expansion (CTE) of the materials utilized in the device fabrication so that thermal transition from ambient to cryogenic operating conditions is embodied in the design.

The majority of the process development and prototype device fabrication activities are being conducted at the University of Central Florida (UCF) through a collaborative research agreement that provides TAI access to facilities, equipment, and staff expertise in critical technical disciplines. There are many challenging aspects in developing the processes and fabrication steps to realize a working expander, but a primary goal from the onset has been to ultimately employ batch semiconductor processing techniques that provide a means to achieve reliable, repeatable, and low cost device production and to facilitate a scale reduction in the device. The prototype expander is nearing completion and component level testing will follow to characterize its performance for validation against our analytical model.

Compressor

TAI is also developing an advanced oil-free floating scroll compressor in collaboration with Scroll Laboratories to provide the DC-flow required for application of the Brayton-cycle in long-life cryocooler systems. Similar compressor technology is being developed for use in medical and fuel cell applications [3]. TABLE 3 lists the primary prototype compressor specifications derived for TAI's Brayton-cycle cryocooler application. The combination of pressure ratio and flow rate required in these systems has not been previously developed in a compressor that is compatible with space service. The primary considerations in TAI's prototype compressor development effort are focused on efficiency, long-life, and contamination resistance. FIGURE 7 illustrates the floating scroll compressor concept.

The floating scroll feature eliminates the prototypical scroll wear mechanisms by balancing the forces and resultant moment on the orbiting scroll while allowing the fixed scroll to translate radially and axially, thereby minimizing contact forces between surfaces.

Table 3. Floating scroll compressor specifications

PARAMETER	VALUE
Pressure ratio	≥ 4.0:1 (Helium)
Lifetime (continuous duty)	10 years
Lubrication	Compression chamber: oil-free Power chamber: confined grease-lubricated
Flow rate	30 slpm
Power source	24 vDC brushless motor
Mechanical efficiency	> 60%
Motor efficiency	> 90%
Mass (includes motor)	3.2 kg (< 2 kg w/o motor or controller)
Vibration	0.5 g

Balance is achieved by configuring two orbiting scrolls mounted from a common base plate and mechanically driving the base plate from the outer edge or from a rigid central hub. Using this method, the forces can be reacted about the base plate producing no net off-axis torque that can contribute to seal or wear. To balance the axial forces that act on the scroll tips, an external gas pressurization scheme is employed. A pressurized gas volume is maintained external from the compression space on the backside of the fixed scroll to apply an axial force. The force on the fixed scroll will then just slightly exceed the separation force acting between the orbiting and fixed scrolls from the compressed gas. This applies a well-controlled, nearly zero force to the tips (that eliminates the need for a thrust bearing), allowing sealing to occur without wear.

Fabrication of the prototype compressor has been completed and preliminary performance testing indicates that the pressure ratio and mass flow rate exceed the specifications. Earlier in the development phase, several compressor heads were fabricated and tested in single and two-stage configurations with helium. This testing confirmed that a two-stage compression approach was favorable for managing the heat generated during the compression process. The prototype unit, shown in FIGURE 8, has two compression stages with intermediate cooling in between. Further performance and life testing is planned to completely characterize this compressor.

Heat Exchangers

The TAI Brayton-cycle cryocooler uses a series of heat exchangers to achieve its thermodynamic efficiency; these include an aftercooler to reject the heat generated in the compression process, recuperative counterflow heat exchanger(s) between the high- and low-pressure gas streams, and cold-end heat exchanger(s) to interface with the element(s) that are cooled. Effective heat exchange in each of the exchangers is paramount to achieving high system efficiency, but the recuperator presents the largest challenge in terms of realizing a compact design that has high net effectiveness. To achieve reasonable

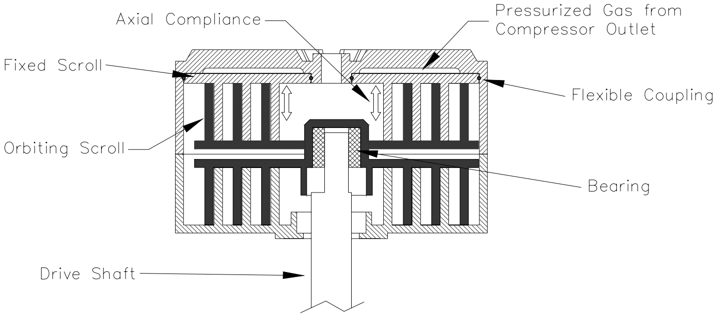


FIGURE 7. Floating scroll compressor features limit net forces and mitigate wear

FIGURE 8. Two-stage floating scroll helium compressor

thermodynamic system efficiency for 10 K and 6 K cooling applications, a recuperator with an effectiveness of a least of 0.97 is required. TAI plans to use compact parallel plate heat exchangers of the type that were initially developed at the National Institute of Standards and Technology in Boulder, CO [4]. These heat exchangers achieve their high effectiveness by using thin stacked parallel plates to separate the gas streams and attain symmetrical flow passages that balance flow across each heat transfer interface. Ball Aerospace is currently fabricating a unique heat exchanger of this type for use in one of TAI's prototype cryocooler systems. Test plans call for the heat exchanger pressure drop and heat transfer characteristics to be measured prior to its integration into the cryocooler.

CONCLUSION

The Brayton-cycle cryocooler technology being developed by TAI provides unique capability that is not available in current state-of-the-art cryocoolers. Successful completion of the present component technology development will enable active cooling solutions that can provide significant benefits to sensor, optical, electronic, and zero-boiloff (ZBO) propellant storage systems that require cryogenic cooling to operate efficiently. While the expander is the key component for enabling TAI's Brayton-cycle cooling technology, the compressor and heat exchanger have application to other systems being developed for long-life operation. An example of this is TAI's Cryocooler Interface System (CIS) that requires a DC-flow compressor to provide remote and distributed cooling from a discrete isolated heat rejection interface [5]. Component and system scalability to smaller configurations has been given significant consideration in the present development by virtue of the design and uniquely applied fabrication approaches.

ACKNOWLEDGEMENTS

TAI would like to thank Thom Davis, Lt. D. Adam Smith, Lou Salerno, Frank Patten, and Dr. K. B. Sundaram for their support and guidance in this development effort.

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