Overview of Micro-Miniature Stirling Cryocoolers for High Temperature Applications

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ABSTRACT

Micro-miniature Stirling cryocoolers for high temperature applications have bee ndeveloped recently to meet market demands. This paper compares micro-miniature Stirling coolers for Higher Operation Temperature applications with a miniature cooler a 2nd FPA base on four cooler subsystems. Thermal dynamics is inherent impetus to size, weight and power, so the regenerator is the key component of the cooler. This paper also presents a novel micro-miniature cooler for Higher Operation Temperature.

INTRODUCTION

Miniature Stirling cryocoolers are widely used in an infrared detector assembly. Since 1980, miniature Stirling refrigerators have been miniaturization with higher efficiency. Micro integral rotary Stirling cryocooler for 2nd generation Focal Plane Array (FPA) operating at 77K-85K usually weigh about 400 g, and split linear Stirling cryocooler weigh 1 kg. Based on miniaturization and optimization performance, micro Stirling cryocooler life has become a critical parameter. The Mean Time To Failure (MTTF) of a linear cryocooler employing a flexure bearing and moving magnet motor is more than 20,000 hours, e.g., THALES and AIM products. The MTTF of a linear cryocooler employing flexure bearing and moving coil motor is 15,000 hours, e.g., DRS products. The MTTF of a rotary cooler exceeds 10,000 hours, e.g., RICOR and THALES [1]. The data is based upon experimental results in laboratory test involving a few sample. The actual MTTF is affected by the environment that the cryocoolers are exposed to. RICOR has tracked their fielded coolers and performed statistical analysis of the K508. MTTF for this cooler reached about 33,000 hours for coolers with static observation, 12,000 hours for hand held devices, and 5,376 hours for armored vehicle [2]. A cold tip temperature of 77K results in a heavy load on the cooler and a reduced life. However, the life of the cryocooler is expected to increase by reducing the load in response to a higher operating temperature.

Higher operation temperature (HOT) FPA detector improves the operating temperature and is beneficial to reduce the load of cooling system, and will benefit the coolers MTTF. Much research

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on high temperature infrared detector have be published in recent years. This trend is driven by the Size, Weigh and Power (SWaP)[3] concept. SWaP[3] is proposed based on the high performance and low cost. The concept means reducing the Size, Weight, and Power with a higher Performance, and lower Price. On the basis of a mature detector structure and state of the art chip preparation, high performance often requires smaller dark current reduced by lower temperature. So it is difficult to reduce the size, weight and power consumption of coolers. HOT detectors rely on new structures and methods of production improving operating temperature [3]. HOT is a promising method to achieve a reduced SWaP.

The 3rd generation MCT focal plane array should work at higher temperature and without losing performance as compared to the 77K performance. This stimulates High Operating Temperature (HOT) MCT detector development. Operating temperature has just an effect on thermal-induced free carriers resulting in noise, and no effect on other performance, such as cut-off wave length and quantum efficiency [4]. A HOT MCT chip can be realized by a new fabrication method and novel structures which suppress thermal-induced carriers. Since 1999, HOT MCT chips truly became commercially viable products, operating at 80K, 90K, 120K, 150K, 175K, 200K [5]. For FPA operating at 77K, the parasitic heat load is the main load. Parasitic loads decrease as the operating temperature rises, and the cooling load also decreases. HOT enables the novel miniature Stirling cooler to reduce Size, Weight, Power, and achieve a longer life of cooler for HOT application.

PRINCIPLES OF MINIATURE STIRLING COOLER FOR HOT

Efficiency of Stirling cooler is the result of four subsystems in total. That is, the overall efficiency is a product of thermodynamic cycle efficiency, mechanical efficiency of drive gear, motor efficiency and electronic work transforming efficiency of control and drive electronic device.

$$\eta_{cooler}=\eta_{cycle}\times\eta_{machine}\times\eta_{motor}\times\eta_{CDE} \quad (1)$$

It is expected to significantly reduce the power consumption of the detector assembly by improving the thermodynamic cycle efficiency with a higher operating temperature. The main reason for thermodynamic efficiency improvement is,

(1) The Coefficient of Performance of a HOT Stirling cooler increases as the operating temperature of the FPA (Te) increases, that is

$$COP_{Stirling}=T_e/(T_{com}-T_e) \quad (2)$$

Since the heat rejected temperature of the compressor (T_{com}) is atmosphere temperature, COP will increase as Te increases.

(2) The specific heat capacity variation of the matrix filled in the regenerator will decrease in a small temperature range. The ratio of the specific heat capacity between the matrix and the gas is greater than a 77K cooler. The larger ratio is beneficial to attenuate temperature hysteresis and improve the heat exchange efficiency in the regenerator. The actual cycle is closer to the ideal reverse Stirling cycle. With a shorter regenerator, there is greater influence by the hysteresis loop. The configuration should be considered for a HOT Stirling cooler.

Comparison Miniature Stirling Cooler for HOT and 2nd Generation FPA

With a cold finger temperature of 95K-200K, the thermodynamic cycle efficiency of a HOT miniature Stilrling cooler is higher than that of 80K coolers for second generation FPA. The reduction in overall efficiency translates into mechanical efficiency, motor efficiency and cooler driver electronics (CDE) efficiency.

Mechanical Efficiency

The unavoidable friction from bearings, piston and other parts in a rotary cooler wastes the partial drive power. The proportion of the friction consumption to total power is higher than those cooler for 80K application. However, linear compressor that rely on contact friction by flexure bearings have an advantage in mechanical efficiency to rotary cooler. The higher operating temperature, the greater the advantage of the linear Stirling cooler mechanical efficiency.

Motor Efficiency

The brushless DC motor for a HOT rotary Sitrling cooler reaches about 70% - 90% efficiency which is comparable to those motor for 80K cooler. The efficiency of a linear motors is individually determined by the design that obviously affects the uniform distribution of the magnetic field.

Frequency of a linear motor for a HOT application rises as a result of lightweight spring oscillator, and this frequency is higher than that for 2nd generation FPA at 80K. Linear coolers by Raytheon for 2nd generation operate at 50-60Hz [6-12], coolers by COBHAM at 54-60Hz [13]. COBHAM LC1076 cooler for HOT operates at 85Hz [14] and RICOR K527 for HOT at 75Hz by comparison.

CDE efficiency

The efficiency of CDE is mainly determined by the efficiency of power transformation module. The novel CDE offers potential for improving efficiency up to 90% in a recent report [15].

Comparison Rotary Cooler and Linear Cooler for HOT

Rotary coolers have several characteristics. They depending upon the rotation speed to regulate cooling capacity, the stroke of piston is constant, and the motor speed which is determined by the input voltage does not involve the thermodynamic cycle and the mechanics. To maintain a specific cryogenic temperature, the rotation speed is regulated and monitored and adjusted in a timely manner for the specified heat load. The principle of the rotary cooler regulation mode is useful for two operating modes, the rapid cool-down mode and the regulation mode for a nominal voltage. A booster promotes the motor speed in cool-down mode to offer the extra cooling capacity to shorten the cool-down time. Nominal input voltage for the optimized frequency increases the motor efficiency.

The operating frequency of a linear compressor is fixed by the natural frequency of spring oscillator. The cooling power of a linear cooler is tuned through changing the linear motor input voltage that dominates the stroke of compressor piston. The stroke of the piston is a key parameter for the thermodynamics cycle and mechanism of the linear cooler. The input frequency and voltage amplitude are inflexible.

The characteristics that the regulation loop bases on the operating frequency and the frequency can be decoupled from thermodynamics and mechanism provides flexibility to Integrated Detector Dewar Cooler Assembly (IDDCA) employed rotary Stirling cooler. Rapid cool-down is compatible with high thermodynamic efficiency through two work mode switch. On the other hand, the linear cooler has some merits that no fraction between the piston and the sleeve extend the lifetime and suppress acoustic noise.

Structure Features on Miniature Stirling Cooler for HOT

The coolers for HOT FPA are significantly smaller than existing products. The reason is that the parasitic load from the dewar decreases as the high operating temperature. The electronics power consumption for a HOT FPA is consistent with the reduction in parasitic load. Cooler miniaturization relies on the smaller swept volume and the smaller motor. The novel product has a small diameter and length for the linear compressor, e.g., 30 mm in diameter and 60 mm in length for the opposed piston compressor, or 40 mm in length for single piston as seen in Table 1. In addition, the regenerator and the cold finger can be reduced due to an increase in thermodynamic efficiency. The cold finger is usually small as shown in Table 1 and Table 2, e.g., 1/4 inch in diameter and 30-40 mm in length. A rotary cooler for HOT can cool down in 3-4 minutes as a result of a booster. It provides an alternative for SWaP thermal imaging system.

Main Aspect of Miniature Cooler for HOT

The cooling capacity (Q) is proportional to the swept volume of the compressor (V_{com}), the charging pressure (P_m), the cold end temperature (T_e) and the operating frequency (f)[19],

Table 1. Typical linear Stirling cooler and Stirling Pulse-Tube cooler for HOT application

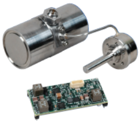
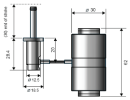
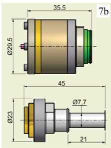
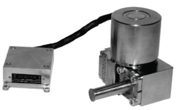
	AIM SX020 [16]	COBHAM LC1076 [15]	THALES UP8197	RICOR K527 [17]	Lockheed Martin STAR [18]
Profile					
Cooling capacity	0.5W@23°C /160K	0.4W@23°C /120K	1.2W@23°C /150K		0.69W@23°C /150K
Compressor	Φ26.5×57.6mm	Φ28.2×53.6mm	Φ30×62mm	Φ29.5×35.5mm	Φ32×90mm
Cold finger	Φ6×27.28 /46.5mm	Φ5×32.1mm	Φ6×30mm	Φ7.6×21 /45mm	Φ9.7×61mm Φ42×50mm reservoir
Weight	240g	260g	250g	140g	328g
Cooldown time		5 min (175J@120K)			8 min (150K)
Temperature range	-54°C～+85°C	-40°C～+71°C			-15°C～+55°C

Table 2. Typical rotary Stirling cooler for HOT application

	RICOR K562S [19]	RICOR K580	THALES RM1
Profile			
Cooling capacity	0.3W@71°C /110K	0.5W@71°C /150K	420mW@20°C /110K
Compressor	34.2×38.5×59.5mm	35×48.2×54.8mm	49.5×50.5×72mm
Cold finger	Φ7.6×45mm	Φ6.1×31mm	Φ6.1×38.5mm
Cooldown time	4 min (160J@110K)	3 min (210J@150K)	4.5 min (110J@110K)
Input power (regulation)	3W@150mW	2W@200mW	2.9W@100mW
Temperature range	-40°C～+71°C	-40°C～+71°C	-40°C～+71°C
Typical assembly	Hot-Pelican MW(640×512) (15μm) 、Kinglet、EPSILON MW(384×288)(15μm)		MW 384×288(15μm)

$$Q= (f/2)\, T_e\, P_m\, V_{com} \times 10^{-5}\ (W) \tag{3}$$

The product of the charging pressure and the swept volume has a positive correlation to the compressor mechanical load which has an effect on the machine lifetime. The high charging pressure is unsuitable for HOT Stirling cooler.

The pressure drop through the generator is negligible. It is thought that the volume of gas in the compression chamber is roughly equal to the volume of gas in the expansion chamber, that

$$V_{com} / V_e = T_{com} / T_e \tag{4}$$

The radius of the compressor piston (R) and the radius of the displacer (r) in the integral rotary cooler has the following relationship,

$$R/r= (T_{com} / T_e)^{1/2} \tag{5}$$

Isothermal model Stirling refrigeration cycle in cold storage caused by the relative dead volume is from 1.8 to 2.5.

The relative dead volume (s) is empirically assumed 1.8 - 2.5 in classic Schmidt's model for Stirling cyrocooler.

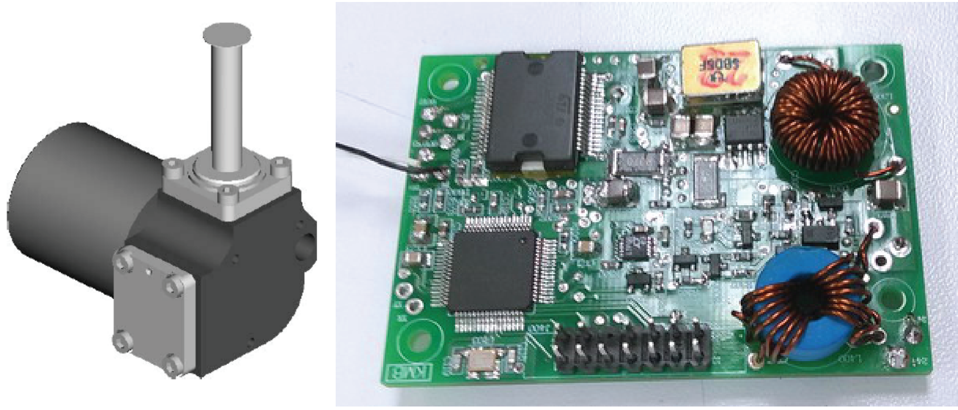


Figure 1. Miniature cooler for HOT and novel CDE

$$s=A_{reg}L_{reg}\Psi/V_{com} \qquad (6)$$

It is worthy to note that the thermal gradient along the cold finger decreases in the HOT miniature Stirling cooler. It is achievable that the novel miniature coolers employ a shorter regenerator and cold finger. A short regenerator us beneficial to reduce the relative dead volume. When the regenerator is shorter, the temperature hysteresis loop becomes more serious. The improvement in COP may not eliminate the temperature hysteresis loop effect. It is important to balance the pressure drop and thermal exchange in the regenerator for a miniature cooler.

MINIATURE COOLER DESCRIPTION IN KIP

The novel miniature cooler is developed for the increasing demand ranging from 120K to 150K in KIP. The principle design of the novel cooler is low charging pressure for the reliability of the bearing and the piston coating. Another design principle is the optimization of the armature and air gap which balances the efficiency and the avoidance of outgassing.

Figure 1 shows the profile of the miniature cooler with a 1/4 inch diameter × 30 mm length. The mass of the cooler is 200 g. At the time of this writing, the prototype is currently being performance tested for optimization. Figure 1 shows the new digital electronics with booster developed for the novel cooler used for HOT application. This electronics has an adjustable booster and 30mK accuracy.

SUMMARY

- Rotary Stirling cooler for HOT is flexible for a the thermal imaging system, in light of the compromise between rapid cool-down and SWaP.
- Linear Stirling cooler for HOT is advantageous for the coefficient of performance, especially higher than 150K.
- Miniaturization of flexure bearing combined with the high frequency linear motor offers the potential for a linear cooler.
- The preliminary rotary Stirling cryocooler and novel electronics with booster are developed in KIP.

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