RICOR's Rotary Cryocoolers Development and Optimization for HOT IR Detectors

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ABSTRACT

The world growth in research and development of High Operating Temperature IR detectors impels the development process and the optimization of rotary crycoolers at RICOR.
The design aspects of size weight and power and the tradeoffs between them, were taken into consideration during the development process in order to optimize IDDCA for future hand held thermal sights.

This paper will present optimization tests results performed for rotary crycoolers at the temperature range of 110 - 200K FPA and also will review the development activities that will be implemented in order to minimize "Idle electronic and mechanical losses," hence minimizing the regulated power consumption.

As a result of the new approach to Rotary crycoolers for HOT detectors, the improvement in the reliability is analyzed and will be reported in the paper.

Keywords: Cryocooler, Rotary integral, Stirling, RICOR, HOT, SWaP, FPA.

1. INTRODUCTION

In the last few years, there has been significant progress of IR detector technology development using (MCT, InSb or other) with High Operating Temperature in the Focal Plan Array called HOT technology. The FPA temperature is known as a key parameter for the cooled infrared detector.
Detector performances like dark current, NETD, number of defective pixels and stability are linked with the operating temperature of the FPA. The technology approach of increasing FPA temperature to HOT range improves cooler thermodynamic efficiency dramatically, which enables optimization for the low power and compact rotary cryocooler.

A compact low power rotary cryocooler compatible with very compact battery packages allows further reduction of the overall thermal imager weight thus making it comparable with the compatible uncooled infrared thermal imager based on a microbolometer detector in terms of power consumption and bulk.

By optimizing the rotary cryocooler for HOT, low input power below 2Wdc and fast cool down time by using digital controller with tunable booster can be achieved.

The optimized cryocooler for HOT is ideally suitable for gyro-stabilized payloads of miniature unmanned aerial vehicles and hand held tactical night vision goggles that often rely on integral rotary micro-miniature closed cycle Stirling cryogenic engines. Lightweight and low power hand held thermal imagers allow improvement in camera features by accommodating additional sensors, like laser rangefinders, target markers or laser pointers.

By moving to HOT detector and reducing Dewar Detector thermal losses, longer life time operation is expected for the camera in the field, hence better life cycle cost.

2. DESIGN ASPECTS

The Coefficient of Performance of a stirling cooler is defined as the ratio between the amount of heat Qe absorbed into the expander and the amount of heat Qc rejected from the compressor. It's also defined as the ratio between the FPA temperature (Te) and the temperature difference between the compressor and the expander (Tc-Te).
Once the (Te) is increased from the known 77K to HOT at 150K, the theoretical Carnot efficiency could be multiplied almost by a factor of 3.
The overall COP of the cooler is a product of partial efficiencies of three subsystems: thermodynamic Stirling cycle efficiency, motor assembly efficiency and driver controller efficiency.

$$\text{(Eq. 1)} \quad COP_{stirling} = Qe / W = Qe / (Wc - We) = Te / (Tc - Te)$$

$$\text{(Eq. 2)} \quad COP_{cooler} = COP_{stirling} * Eff._{motor} * Eff._{controller}$$

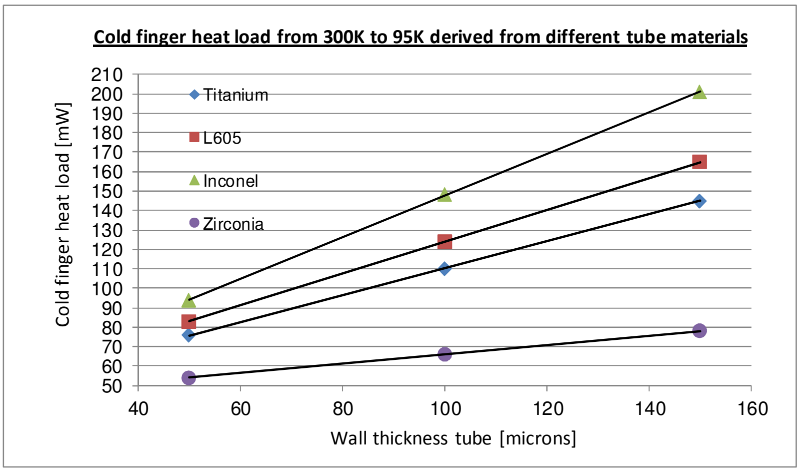
As a result, the striling thermodynamic cycle for a HOT range of 110-200K is found to be optimal while the thermodynamic COP increases with small changes in the FPA temperature.
Moving into HOT detectors and developing a derivative or new cryocooler gives opportunities to deal with several design aspects from the $SWaP^3$ – Size, Weight, Power, Performances and Price as well.

As a preliminary characterization for a cooler optimized to HOT temperature, the following parameters were analyzed during the design phase:

1. **An FPA temperature** in the range of 130K÷180K while 150K seems to be the most typical value.
2. **A Power consumption** of IDDCA lower than 2Wdc during regulated mode at room ambient temperature. Cooler power budget needs to be lower than 1.5Wdc including the electronic controller consumption.
3. Priorities in the **$SWaP^3$** depend on the application type. The tradeoffs between size, weight, power, performances and price were well analyzed.
4. Form **reliability** considerations, fill pressure dramatically reduced in order to reduce the load level on cooler bearings. As a result of the fill pressure reduction, the booster voltage level needs to be optimized in order to accelerate the operating frequency during cool down only.
5. **The cold finger** optimized by materials, geometry and manufacturing process in order to reduce cold finger size and self-heat load.
6. **Input voltage** - the electronic controller and cooler motor were designed to operate at low voltages in the range of 6-7V in order to save power at camera level mainly when powered by batteries.
7. **The electronic controller** will be designed and optimized for HOT with efficiency design goal of 90% as part of the system FPGA processor in order to save power.

The tradeoffs between cold finger stiffness to sustain mechanical environmental conditions, heat load by conduction & radiation and cold finger length were analyzed in order to optimize for HOT applications.
For applications where the **size** is dominant, the cold finger shortened by half its size and the regenerator shortened and optimized respectively. A short K562S derivative version developed based on a cold finger that was shortened from 45mm to 22.5mm, reducing the cooler size in the critical optical axis from 79.2 mm to 56.7mm. In order to compensate for the heat load increase by conduction, a new design based on a titanium tube which excels in low thermal conductivity developed. Such an approach enables to incorporate the cooler in a smaller volume such as a miniature gimbaled payload.
For applications where the **Power consumption** is dominant, the cold finger wall thickness tube is reduced from the range of 80-100µm to the range of 50-60µm.

New process of cold finger polishing will be analyzed in order achieve Emissivity level of 0.1 hence reduce thermal radiation between the outer Dewar envelop and cold finger tube.



Graph 1: Heat load study review for different cold finger tube materials

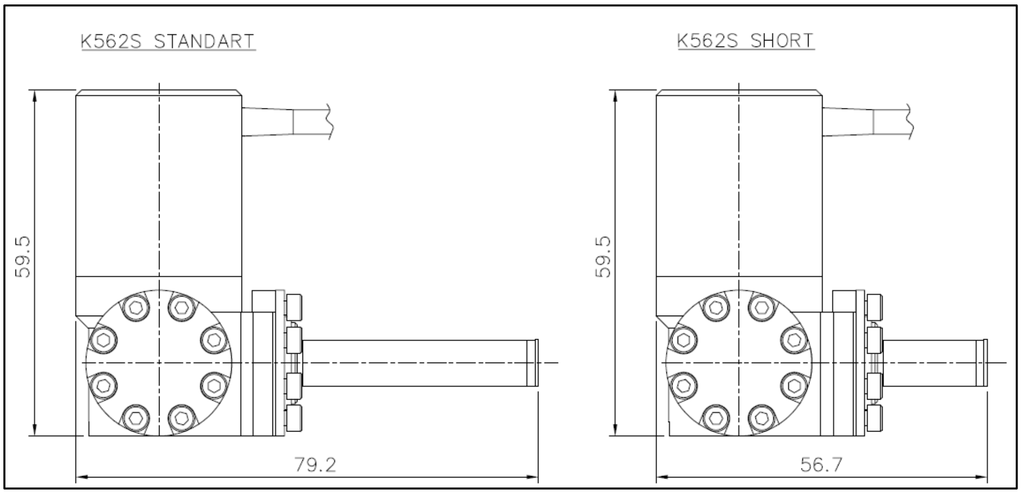


Figure 1: K562S standard Vs. K562S short derivatives for HOT applications

By studying the power consumption fractions of a rotary cooler while it operates without load, it was learned that about 90% of the power consumption related to the compressor & rotor assembly operates in idle current only. The conclusion from the study was that power consumption could be improved by optimizing the mechanical construction & motor assembly.

The following parameters will be analyzed in the next phase of the development in order to reduce as much as possible the idle current:

1. Bearing size reduction
2. Grease type and quantity optimization
3. New type of Bearings Implementation
4. Dynamic clearances optimization
5. Bearing clearances and preloading forces optimization

In order to cope with a very compact bulk mainly at small gimbaled systems when the size is more dominate than the power consumption, K562 model weighting 135gr could be integrated with short cold finger based on titanium tube or L605 with 50µ wall thickness.

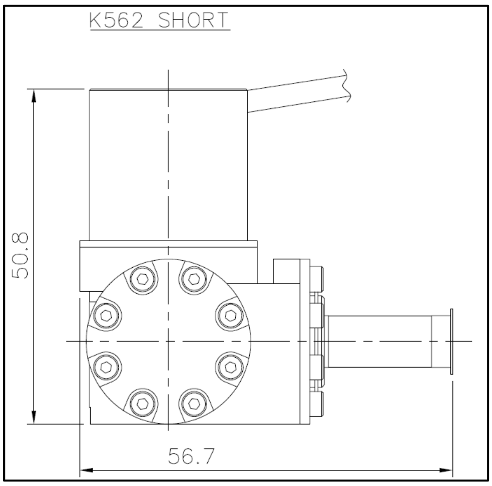


Figure 2: K562 short weighting 135gr for HOT gimbaled systems

As part of rotary cooler integration in a system with HOT detector, few design aspects optimized:

1. Implement soft start by digital controller to reduce dramatically the maximum peak power hence better compactness for the power source.
2. Design the electronic digital controller and the motor windings according to a battery typical voltage such as 2 cells x3.6V in order to eliminate voltage transformation losses at system level.
3. Efficient heat removal from the compressor, motor and controller to keep temperature gradient lower than 5 degrees from ambient.

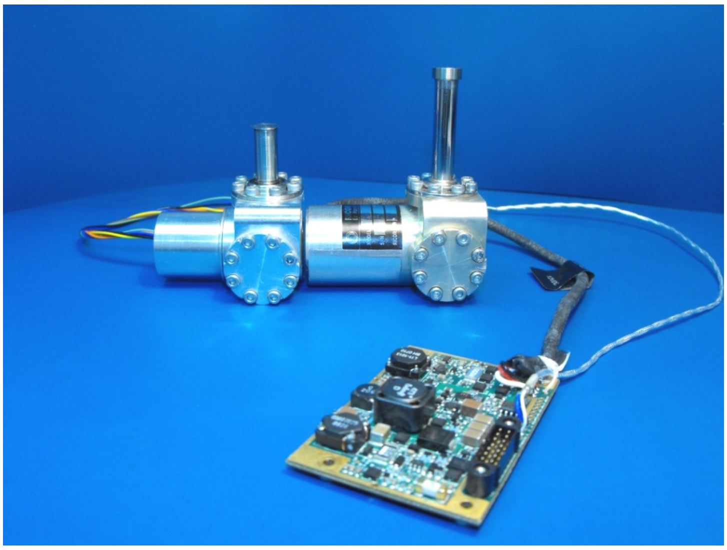
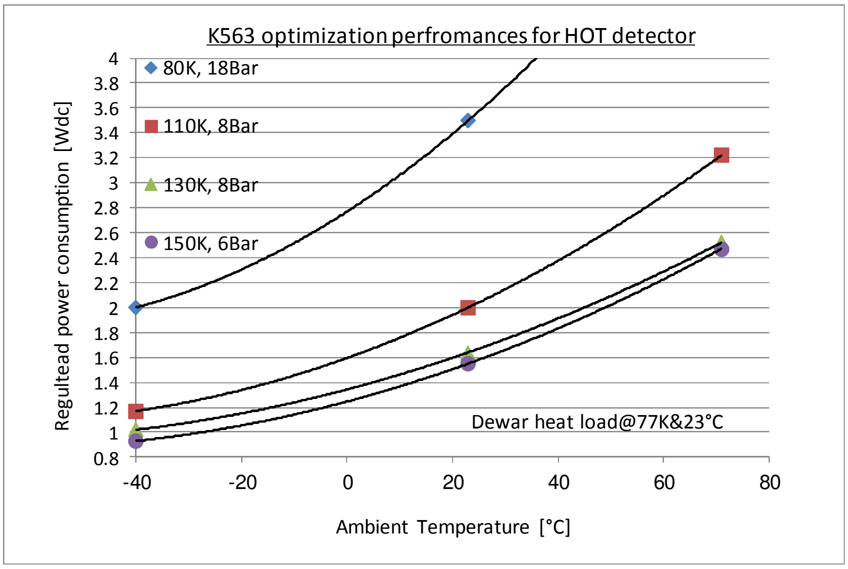


Figure 3: K562 short Vs. K562S standard with digital controller

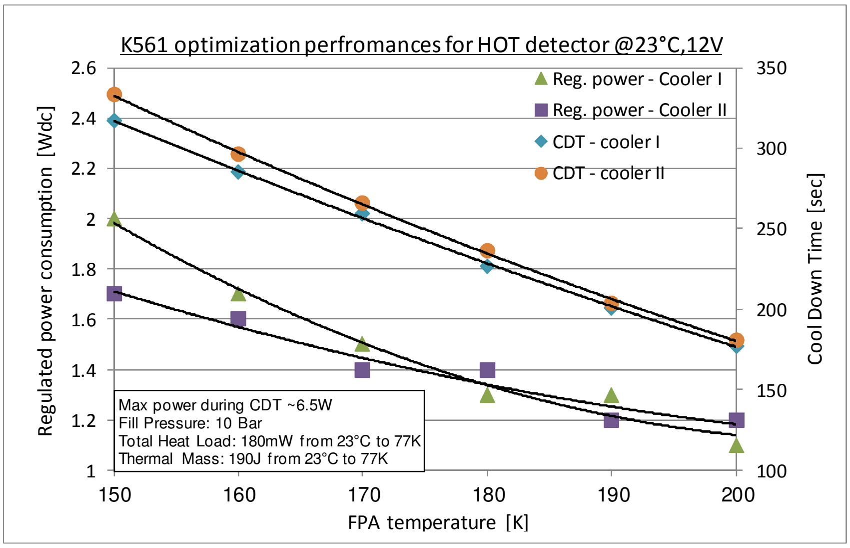
3. CRYOGENIC PERFORMANCES FOR HOT DETECTOR

By moving from a tactical 77K FPA temperature to HOT temperature range between 110K to 150K, a dramatic reduction in the cooler fill pressure achieved from 18Bbar to 6-8Bar in K563 model. Experimental test performed from one hand at low ambient temperature of -40°C to ensure cooler rotation at low frequency of 18-19Hz and from other hand sufficient cooling power redundancy at 71°C ambient.
A regulated dc power consumption of 1.55-1.64W measured at room ambient in the FPA temperature of 130-150K.



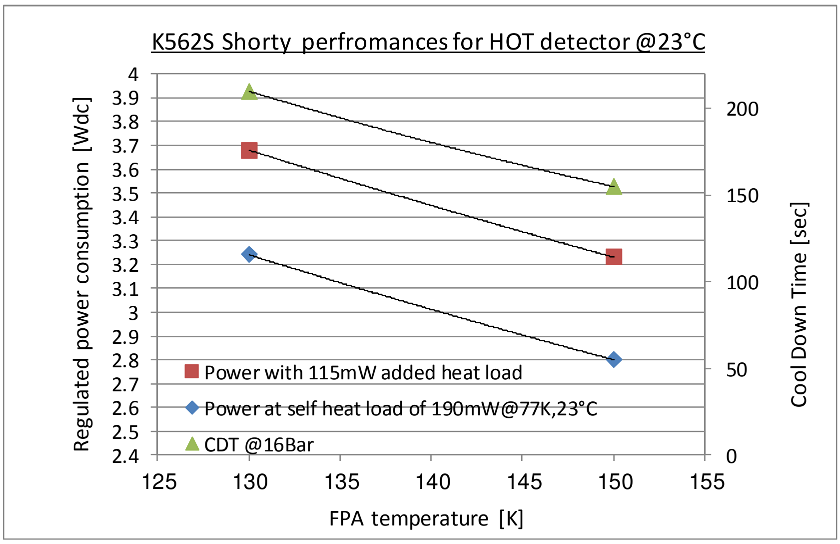
Graph 2: K563 optimization at different FPA temperatures and fill pressures

Fill pressure reduction performed also for K561 model from 20Bar typical to 10Bar. Performances mapping had done for cool down time and dc regulated power consumption in the FPA temperature range of 150-200K. Regulated power consumption lower than 1.2W measured at 200K & 23°C.



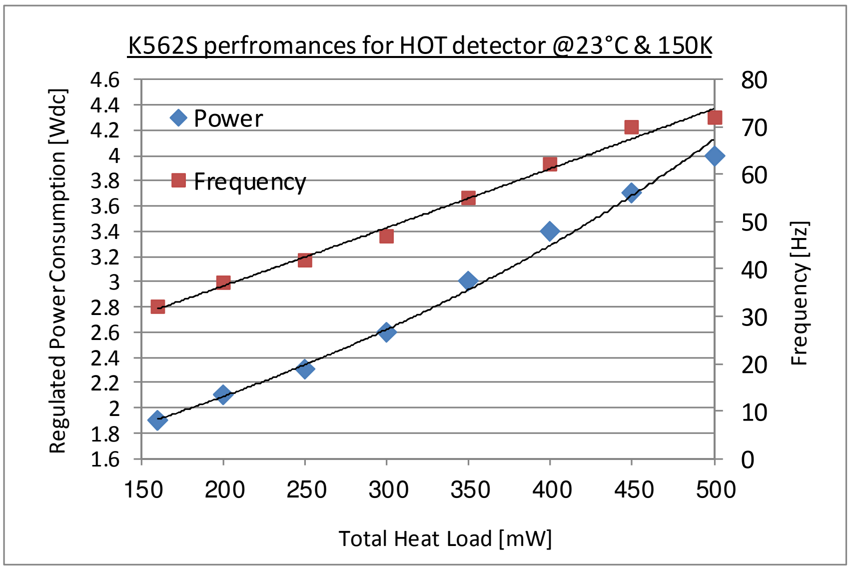
Graph 3: K561 optimization for FPA range of 150-200K

K562S short model with a reduced fill pressure from 20Bar typical to 16Bar tested at FPA temperature range of 130-150K. A short cool down time achieved due to the reduced self thermal mass of the cooler derived from the shorten regenerator. There is a tradeoff in regulated dc power consumption once moving from standard cold finger to short cold finger.



Graph 4: K562S short optimization for FPA range of 130-150K

Performances mapping done for standard K562S at 150K in order to evaluate the cooling power at different heat loads. Dc regulated Power consumption of 1.9W measured at 160mW heat load & 32Hz and cooling power higher than 1/2W measured at room ambient.



Graph 5: K562S mapping for FPA of 150K

4. RELIABILITY EVALUATION

The prediction model of a rotary stirling cooler is a multiplication one, where the actual MTTF (θ_{PR}) of a given cooler type subjected to prescribed working conditions is computed by multiplying a basic MTTF value (θ_b) derived from a life test or field data by a series of conversion factors (π). These factors quantify the sensitivity of the basic MTTF to the alteration in working conditions from the reference to the actual conditions.
The prediction model is:

$$\text{(Eq. 3)} \quad \theta_{PR} = \theta_b \pi_E \pi_T \pi_{S1} \pi_{S2} .....$$

Where:

θ_{PR} - Projected MTTF
θ_b - Basic MTTF
π_E - Environmental factor
π_T - Ambient temperature factor
π_{Si} - Stress i conversion factor

The working stresses conversion factors are the cooling gas pressure (P) and the operating frequency (H) which is derived from parameters such as thermal load and FPA temperature.

Thus:

$$\text{(Eq. 4)} \quad \theta_{PR} = \theta_b \pi_E \pi_T \pi_P \pi_H$$

The factors π_P , π_H are computed according to the inverse power law as follows:

$$\text{(Eq. 5)} \quad \pi_P = \left(\frac{P_b}{P_{PR}} \right)^2 , \ \pi_H = \left(\frac{H_b}{H_{PR}} \right)^2$$

Where b and PR stand for the working conditions at the reference and actual working points accordingly.

The theoretical formula for bearing life calculation with 90% probability:

$$\text{(Eq. 6)} \quad L_{10} = A_1 \cdot A_2 \cdot A_3 \cdot \frac{1}{P^3} \cdot \frac{C_1}{N^1}$$

Based on RICOR life demonstration test and analysis, the following formula used for bearing life calculation:

$$\text{(Eq. 7)} \quad L_{10} = A_1 \cdot A_2 \cdot A_3 \cdot \frac{1}{P^2} \cdot \frac{C_1}{N^2}$$

As a result, the improvement in K563 MTTF due to fill pressure reduction from 18Bar to 8Bar at 110K based on Eq. 7 will be:

$$\text{(Eq. 8)} \quad \left(\frac{P_1}{P_2} \right)^2 \cdot \left(\frac{N_1}{N_2} \right)^2 = \left(\frac{18bar}{8bar} \right)^2 \cdot \left(\frac{14Hz}{28Hz} \right)^2 = 1.26$$

The contribution of FPA temperature higher than 110K needs to take into consideration separately for the MTTF improvement evaluation due to the operation in lower frequency level.

5. SUMMARY

A new approach was achieved in the range of rotary cryocoolers development and optimization for HOT detectors thanks to several novel technologies implemented in RICOR crycoolers.

For the short term development of HOT detectors, few existing cryocoolers models optimize for HOT while taking into consideration SWaP design aspects. By reducing dramatically the fill pressures and by implementing new cold fingers such as short versions, new cryocoolers derivatives well adapted to new IR systems based on HOT detectors.

For the mid and long term development of HOT detectors, further optimizing will be performed in the compressor mechanical system in order to reduce idle current and also by high efficient controller development as part of the system electronic. In parallel, new cryocoolers concepts under development consideration in order to achieve further approach with SWaP design aspects.

As a summary, RICOR's rotary crycoolers well optimized for the new trend of IR detectors based on HOT technology while further development of cryocoolers planned for the next future.

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