Linear cryogenic coolers for HOT infrared detectors

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ABSTRACT

In spite of a wide spreading the uncooled night vision technologies, the cooled systems are still known to be superior in terms of working ranges, resolution and ability to recognize/track fast moving objects in dynamic infrared scenes.

Recent technological advances allowed development and fielding of high temperature infrared detectors working up to 200K while showing performances typical for their 77K predecessors. The direct benefits of using such detectors are the lowering of the optical, cooling and packaging constraints resulting in smaller and cost effective optics, electronics and mechanical cryocooler.

The authors are formulating requirements and general vision of prospective ultra-compact, long life, lightweight, power efficient, acoustically and dynamically quiet linear cryogenic cooler towards forthcoming infrared imagers.

In particular, the authors are revealing the outcomes of the feasibility study and discuss downscaling options.

Keywords: HOT detector, micro-miniature linear cryocooler.

1. INTRODUCTION

Readiness of night fighting capabilities is one of the critical components forming the decisive superiority of the Western military and antiterrorist forces. By converting the thermal battlefield into a dynamic visual imagery, such equipment dramatically enhances the observation and command control capabilities. It is widely believed today that low-level night vision equipment needs to be deployed not only with the leaders of combat units but with each and every soldier.

In spite of the recent advances and widespread use of uncooled infrared (IR) technology it is still generally acknowledged that the "best technology for true IR heat detection is the cooled detectors" [1]. They are superior to the uncooled rivals in terms of working ranges, resolution and ability to detect/track fast moving objects in dynamic infrared scenes. The superior performance of such imagers is achieved by using advanced optronic technologies along with maintaining the IR detector at cryogenic temperatures (77K, typically) using mechanical closed-cycle Stirling cryogenic coolers. Unfortunately, such imagers appear to be too expensive in buying and use, too bulky, too power thirsty, too noisy and not reliable enough for a massive deployment. Along with these lines, additional preventing factor is awkward batteries supply/recharge logistics.

Over the past few years industrial progress has led to the development of a new Mercury Cadmium Telluride (MCT) ***n/p*** and ***p/n*** technology [2,3] offering the possibility to operate IR detectors at essentially higher temperatures (up to 200K) while showing good performances in a middle wavelength (MW) blue band, MW and long wavelength (LW) at extremely low rate of defective pixels.

More complex ***nBn*** infrared detector architecture is a relatively new detector concept. It was first introduced by Maimon and Wicks [4] and has surprised many with both simplicity and level of performance [2,3]. This technology shows good potential to operate at even higher temperatures. It is not a surprise, therefore, that major players, including DRS Technologies, Raytheon, Teledyne, Sofradir, Selex Galileo, AIM and SCD continue exploring existing and future MCT opportunities (see for example, http://drs.com/Products/RSTA/PDF/MCTBenefits.pdf).

The direct benefits of using such high operational temperature (HOT) IR detectors are the lowering the optical, cooling and heat sinking constraints. This results in simplified and more compact night vision instrumentation allowing using, in particular, forthcoming low power, micro-miniature, cost effective, long life and acoustically quiet mechanical cryocoolers.

Traditionally, integral rotary cryogenic coolers were used for maintaining the 77K focal plane arrays (FPA) of the IR imagers at optimal cryogenic temperatures. As compared to their linear rivals they were less expensive, lighter, more compact and normally had better electromechanical performance.

Increasing regulated temperature results in drastic power draw reduction. Sofradir reported on testing their Scorpio detector integrated with Thales RM2 integral rotary cooler [3]. In particular, for a standard Helium charge pressure and under standard environmental conditions, with FPA temperature increase from 90K to 150K the authors observed 45% reduction in power consumption (from 4.0 to 2.2 W AC). The similar testing performed with Ricor's integral rotary cooler revealed in excess of 60% power draw reduction. This may be explained primarily by about 65% improvement of the Carnot coefficient of performance resulting from increase of the cold (acceptor) temperature from 90K to 150K at the same (+27°C), heat sink (reject) temperature.

Unfortunately, integral rotary technology appears to be quite limited in terms of further size, weight and power (SWaP) reduction. To start with, their compact double crank sliding linkage featuring miniature ball bearings and driven by a DC brushless motor already exhausted its downscaling potential. Further, at small heat loads, the inherent (primarily mechanical) parasitic losses appear to be comparable with the overall power consumption. These are: (i) friction in ball/needle bearings and in tight clearance seals (piston-cylinder and bushing-plunger) and (ii) Copper losses in the motor winding comprising relatively large parasitic lobe portions as typical for small DC brushless motors.

Additional known drawbacks of the above technology are related to the FPA temperature control method relying on the variation of driving speed. As is known, both thermodynamic and electro-mechanic efficiency are frequency dependent and show well distinguished optimum at the particular working frequency. The departure of said working frequency from the said optimal value results in overall performance deterioration.

Figure 1 shows, for the reference, typical dependencies of the **net** (AC) steady state power consumption on the added heat load (further - load curves) at different stabilization temperatures (150K and 170K). This data was obtained during testing of standard Ricor integral K561 rotary cooler at normal reject temperature +27°C. From Figure 1, both load curves show typical flat portions ranging from zero to 50mW (150K) and 100mW (170K). This might be explained by the domination of parasitic losses over the useful "shaft power".

Further inherent known drawbacks of rotary integral technology are high vibration export associated with double-frequency oscillations of driving torque and micro-impacts occurring in the clearances of the above double crank slide linkage, high frequency noise, limited lifespan and awkward packaging associated with fixed spatial orientation of compressor and expander portions of the cooler.

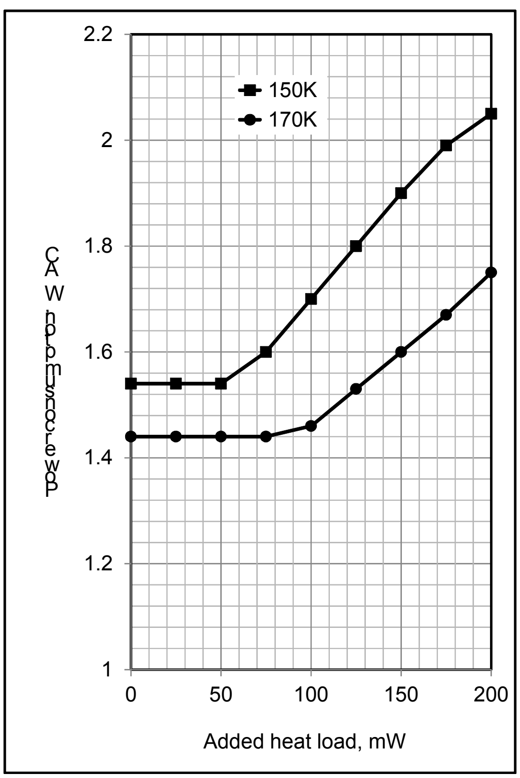


Figure 1. Typical load curves of rotary integral cooler

The above explained limitations of the rotary integral technology have spurred the development of the microminiature linear Stirling cryogenic coolers towards forthcoming high temperature IR detectors. Ricor model K527 long-life, acoustically and dynamically quiet split Stirling linear cooler has been originally designed for 95K FPAs [5-9]. This cooler features resonantly "moving magnet" single-piston compressor and pneumatically driven resonant expander. It is the smallest in the market split linear Stirling cooler having, however, superior performance indices [5-9]. It also appeared to be comparable to the above mentioned rotary cryocoolers in terms of bulk, power consumption and ownership costs. Known advantages of the linear technology, as compared with the rotary one, are as follows:

Reduced friction losses in compressor and expander

Both compressor and expander units are driven by linear electro-dynamic and pneumatic actuators. There is no need, therefore, in transforming rotary into linear motion. This eliminates essential portion of parasitic mechanical losses typical for the rotary technology, relying on double crank sliding linkages, ball bearings, etc.

Reduced Copper losses
The active Copper winding of a linear electro-dynamic actuator is fully located inside the return iron and contains no parasitic lobe portions which are typical for the rotary DC brushless motors, as normally used in integral rotary coolers. This results in actuator having inherently higher electromechanical efficiency.

More efficient and flexible control strategy allowing constant and optimal frequency operation
The linear cooler works at constant and optimal frequency, while the magnitude of the applied driving voltage varies in according to the required heat lift. This allows maintaining the optimal working conditions for all times. Additional factor is that the performance of linear electro-dynamic actuator may be optimized towards chosen driving frequency.

Improved life expectancy
Operation of linearly driven components in compressor and expander is normally smooth and is not associated with significant side forces and micro impacts which are typical for operation of crank slider linkage as used to transform the rotary into linear motion in an integral rotary cooler. Along with these lines, in linearly driven compressor there is no need in the greased ball/needle bearings which are known to be the critical components in the rotary technology. This leads to extended cooler life, ranging normally up to 30,000 hours instead of 10,000 hours which are typical for their rotary rivals.

Flexibility in IR imager packaging and heatsinking.
Split design normally offers more flexibility in imager packaging and heatsinking.

Aural non-detectability
Because of the smooth, impact-free reciprocation of the moving assemblies, the vibration export does not contain higher order harmonics and normally does not result is structural noise. From experience, the noise produced by IR imager containing linear cryocooler (2 meters measurement distance) is comparable with the background noise in hemi-anechoic chamber per MIL-STD 1474D.

Better downscaling potential
The linearly actuated compressor and pneumatically actuated expander are literally free of bearings and motion transformation mechanics. This allows the inherent mechanical simplicity and better potential for downscaling, as compared with the rotary technology.

Based on previously acquired multi-year experience, proven technologies, thorough thermal and dynamic analysis the authors are attempting to downscale the Ricor type K527 [5-9] cryogenic cooler. They report on mapping the K527 cooler having regular and shortened cold fingers at the typical acceptor temperature 150K. Further, they perform verification of the numerical SAGE model, optimization of the cooler for the new working conditions and present the predicted load curves. Finally, they present the design outline and discuss vibration issues.

2. DESIGN PRINCIPLES AND PERFORMANCE MAPPING OF RICOR K527 CRYOGENIC COOLER

Ricor recently reported on the successful development and fielding of the novel model K527 microminiature long-life split Stirling linear cryogenic cooler [5-9] for use in a wide range of portable hand held and gyrostabilized infrared imagers. Technical comparison [5-9] to coolers of the same cooling power at 80K@23°C indicates that this cooler is the smallest, lightest and most efficient over the range of "one watt" linear coolers.

Because of the tight constraints imposed primarily on weight, price and cooling performances, the design of this cooler largely abandons the fashionable features such as flexural bearings, contactless dual-piston compressor, computerized assembly [11], etc in favor of mechanical simplicity and SWaP improvement.

In particular, the compressor design relies on a "moving magnet" resonant single-piston concept featuring a very light (0.035kg) "magnet–piston" assembly guided by a precise contact clearance seal made in the form of tightly matched (5 μm radial gap) piston-cylinder liners manufactured of tribological, wear-resistant material.

Similar principles were applied to the expander design. First, Ricor accepted the concept of pneumatic actuation of the resonant “mass-spring” displacer-regenerator and clearance seals in the form of contact, tightly matched (4 μm radial

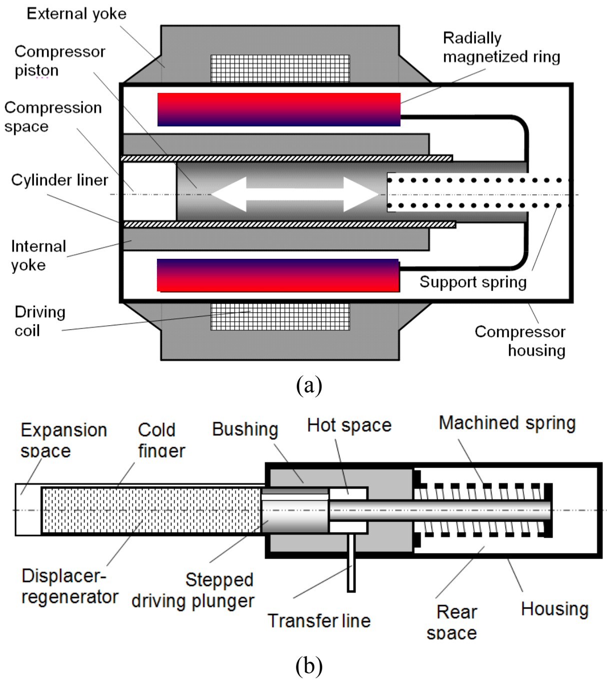


Figure 2. Schematic of a linear compressor (a) and pneumatically driven expander (b)

gap) dynamic seals made of the above tribological, wear-resistant material. Machined springs were used to minimize fretting-induced debris generation, side forces and, therefore, seals wear. The feasibility of this approach was proven recently in the course of an accelerated life test (including temperature extremes) [10], where a similar cooler lasted in excess of 45,000 hours. The "postmortem examination" revealed that the geometry of the above mentioned critical components (i.e contact clearance seals in compressor and expander) remained within manufacturing tolerances. No visible wear was observed.

The self-explanatory Figure 2.a shows the schematics of a linear compressor. The radially magnetized ring is placed movably between the stationary internal and external armature yokes which are made of magnetically soft material. The yokes are shaped to accommodate the driving coil carrying the AC current and to provide for quasi-uniform distribution of the magnetic flux within the working air gap without over-saturating the yoke's material. The magnetic ring is formed by magnet segments bonded upon the cylindrical magnet form, which is, in turn, rigidly attached to the compression piston being movably placed inside a tightly matched cylinder liner arranged within the bore of internal yoke. For the sake of compactness, a double-starting helix machined spring with integral retainers connecting the movable piston and stationary housing is placed inside the piston.

The self-explanatory Figure 2.b shows the schematics of the pneumatically actuated expander of the K527 cryogenic cooler [5-9]. The expander unit comprises a "mass-spring", resonant and pneumatically driven displacer-regenerator, as is widely accepted across the industry. The regenerator is formed as a stack of fine stainless steel screens encapsulated inside the plastic tubular liner, thus forming the displacer-regenerator assembly which, in turn, is attached to the stepped driving plunger.

The bushing and the cold finger tube are accurately aligned relative to the central bore of the housing. In the present design, the authors capitalize on using a highly accurate, zero side force double-starting helix machined spring with integral retainers. The purpose of the above spring is to ensure the moving assembly centering and delivering the favorable resonant properties. The bushing and driving plunger are tightly matched to 4μm radial clearance and made of highly wear-resistant material.

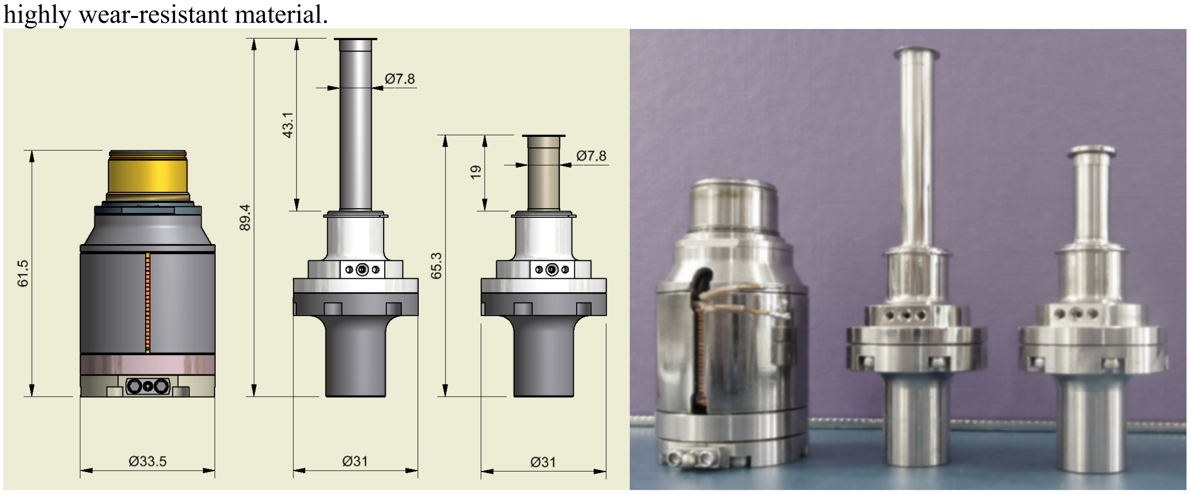


Figure 3. External layout and pictures of the linear K527 compressor, regular and shortened cold fingers

Figure 3 shows the external layout and pictures of a linear compressor, regular and shortened cold finger "Shorty" which has been designed for compact gyro-stabilized IR applications relying on HOT (130K) detectors [6]. It features a cold finger shortened from 43mm to 19mm.

Performance mapping of the K527 cryogenic cooler including regular and short cold finger working in a temperature control mode 150K has been performed at normal ambient temperature +23°C, the typical reject temperature was +27°C. The self heatload of the typical simulation Dewars are approximately 105mW@150K@27°C and 190mW@150K@27°C for the regular and shortened cold fingers, respectively. Both coolers were loaded by a typical thermal mass 180J@150K→300K. These are the typical values for the materials, geometry, emissivity factors and thermal inertia of the existing cold fingers and evacuated envelopes.

Figure 4 shows the dependencies of the power draw versus added heat loading ranged from 0 to 1000mW (load curves) of regular and "Shorty" K527 cooler working at the above explained conditions.

Figure 5 shows the typical dependence of the AC power consumed by the K527 cooler with regular cold finger on the acceptor temperature at different added heat loads ranging from 0 to 100mW. It is important to notice that, unlike with a rotary cooler, lowering the heat lift demand for the linear cooler results in proportional reduction of the power consumption, both in terms of acceptor temperature and added heat load. This indicates practical absence of parasitic mechanical losses.

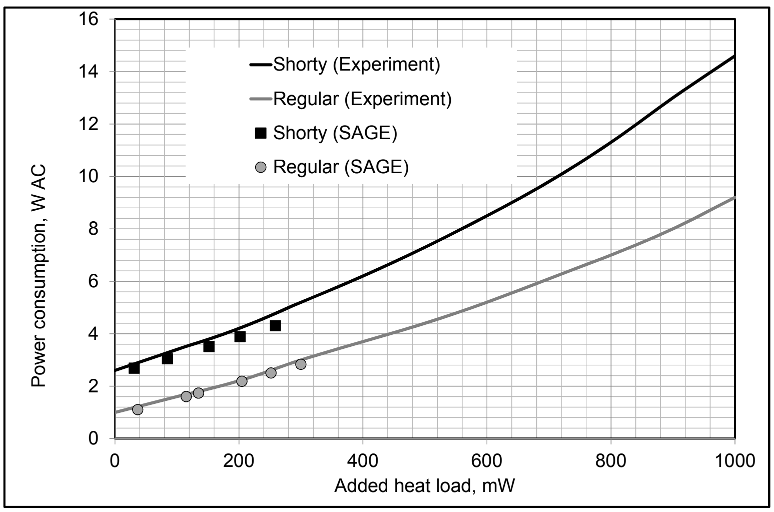


Figure 4. Load curves for the K527 cryocooler with regular and shortened cold fingers

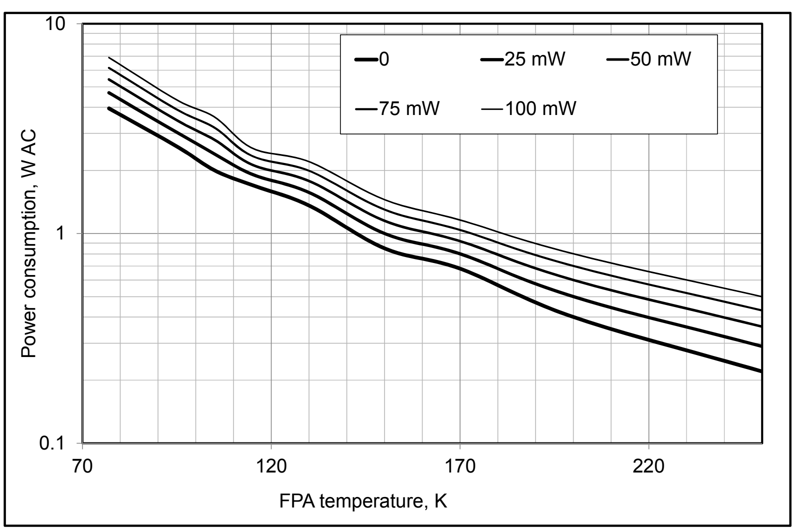
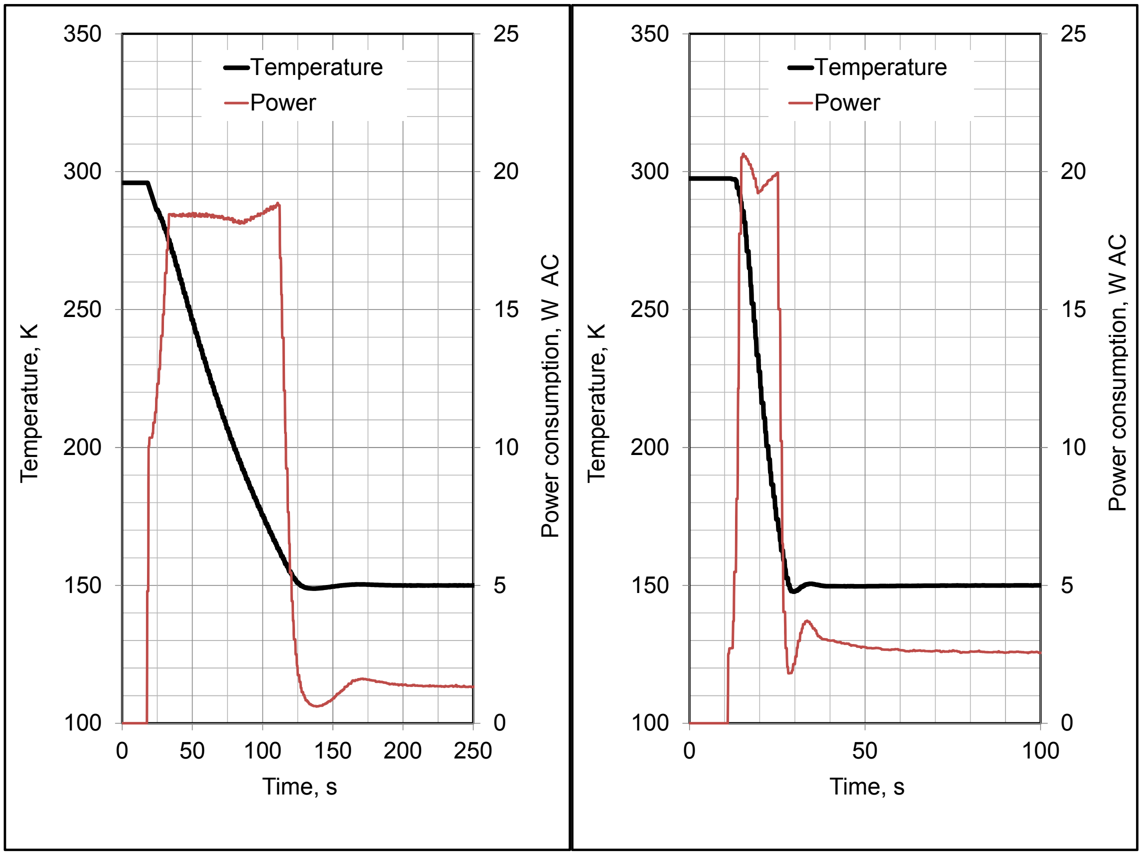


Figure 5. Typical dependencies of the power consumption on the FPA temperature at different added heat loading

Figure 6 shows typical dependencies of the temperature and power consumption during the cooldown phase. From Figure 6.a (case of regular cold finger), the cooldown takes 1:45 min; maximum power draw in the end of the soft start is 18.5W AC. From Figure 6.b, (case of shortened cold finger), the cooldown takes 0:30 min; maximum power draw in the end of the soft start was 20.5W AC.



(a) (b)

Figure 6. Cooldown curves in cases of regular (a) and shortened cold finger (b)

6. SAGE optimization for 150K

Important to notice now is that the maximum power consumption of the K527 cooler is 30 W AC. With the regular cold finger it provides heat lift (added) 1000mW@150K@27°C at 9W AC, shortening cold finger results in power increase at this working point up to 15W AC. This indicates that K527 cooler with both regular and shortened cold fingers are overkill solution for the typical requirement 100mW@150K@27°C; further downscaling is beneficial.

Prior to the cooler reshaping for the new, 150K working point, we can make a couple of justified assumptions. To start with, the requirement of extra low power consumption is applicable mostly to the battery powered hand held imagers, which are normally operated in a very mild, literally free of shock and vibration, environmental conditions. That is why, without compromising cold finger integrity and based on the proven technology, we can reduce the wall thickness of the cold finger from the standard 0.08mm to 0.05mm; this results in reducing conductive losses by approximately 20mW@150K@27°C and 34mW@150K@27°C for the regular and shortened cold finger, respectively.

Further, electro polishing and gold plating the evacuated envelope interior allow for lowering the emissivity factor down to 0.04 instead of typical 0.2. This reduces radiation losses by approximately 40mW@150K@27°C and 28mW@150K@27°C for the regular and shortened cold fingers, respectively. The combined effect of thickening cold finger wall and polishing/gold plating of the Dewar interior produces approximately 60mW@150K@27°C heat load reduction for both regular and shortened cod fingers.

In doing downscaling, we may expect not only improving size and weight indices, but also reducing power consumption by eliminating parasitic dead volumes, choosing proper charge pressure, regenerator material/geometry and driving frequency.

To start with, we decided to downscale the compressor unit only and to keep the external geometry of the regular cold finger. The optimization goal was to minimize the power consumption at the above working point (100mW@150K@27°C), by varying the regenerator material and porosity, charge pressure and driving frequency. In doing so, we found out that the swept volume in compressor needs to be 4-fold reduced, the new optimal driving frequency needs to be 50Hz instead of 77Hz, charge pressure needs to be 20bar instead of 15bar, the regenerator material might be #535 mesh SST screens made of Ø25μm wire; the optimal porosity will be 75%. In simulation, we assumed that the mass of the piston assembly will be reduced from 35gr to 20gr and the linear actuator force/current factor will be 3.5N/A, similar to this of regular K527 compressor actuator. In all simulations we also assumed that the cold finger thickness will be 0.05mm and emissivity of Dewar interior walls will be 0.04.

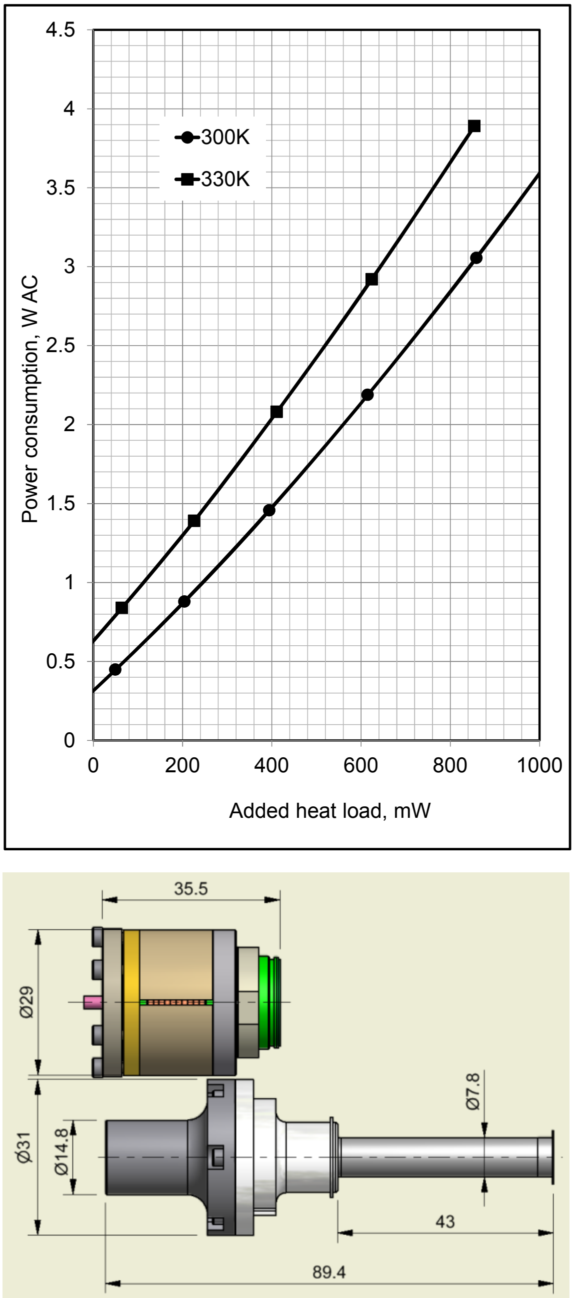


Figure 7. Predicted load curves and preliminary design outline of the downscaled cryogenic cooler with regular cold finger

Figure 7 shows the 150K load curves predicted by the SAGE simulation software for the optimized cooler at different reject temperatures typical for the working range of hand held IR imagers, namely: 27°C and 57°C. From Figure 7, the power needed at the specified working point 100mW@150K@27°C will be as low as 0.6W AC; the power consumption will rise to 1W AC at 57°C. It is important to notice that the obtained cooler is capable of delivering up to 1000mW heat lift with power consumption below 4W AC. This indicates further downscaling potential.

Figure 7 also shows the initial design layout of expander and compressor units, where the external layout of the expander unit is similar to this of the regular K527 cryocooler. The compressor unit is much downscaled, as compared with K527 (see Figure 3). From models, the compressor weight is only 110gr, this is approximately half of this in K527. The entire cooler weight will be, therefore, 180 gr. Further mass and size reduction will be possible as a result of transition to all-welded approach; the detailed discussion is beyond the scope of this paper.

Further, we attempted to optimize the shortened expander. The optimization goal was again to minimize the power consumption at the above working point (100mW@150K@27°C), by varying the cold finger ID, regenerator material and porosity, piston OD, charge pressure and driving frequency. In doing so, we found out that the swept volume in compressor needs to be again 4-fold reduced, the new optimal driving frequency needs to be 50 Hz instead of 90Hz, charge pressure keeps being 15bar, the cold finger ID needs to be 6.1mm instead of 7.8mm, the regenerator material might be #635 mesh SST screens made of Ø20μm wire; the optimal porosity will be 67%.

In simulation, we assumed that the mass of the piston assembly will be reduced from 35gr to 20gr and the linear actuator force/current constant will be 3.5N/A like this of regular K527 compressor actuator. In all simulations we again assumed that the cold finger thickness will be 0.05mm and Dewar interior wall emissivity will be 0.04.

Figure 8 shows the 150K load curves predicted by the SAGE simulation software for the optimized cooler at different reject temperatures typical for the working range of hand held IR imagers, namely: 27°C and 57°C. From Figure 8, the power needed at the specified working point 100mW@150K@27°C will be as low as 1.2W AC; the power consumption will rise to 1.8W AC at 57°C. It is important to notice that the obtained cooler is capable of delivering up to 1000mW heat lift with power consumption below 7W AC. Figure 8 also shows the initial design of expander and compressor units.

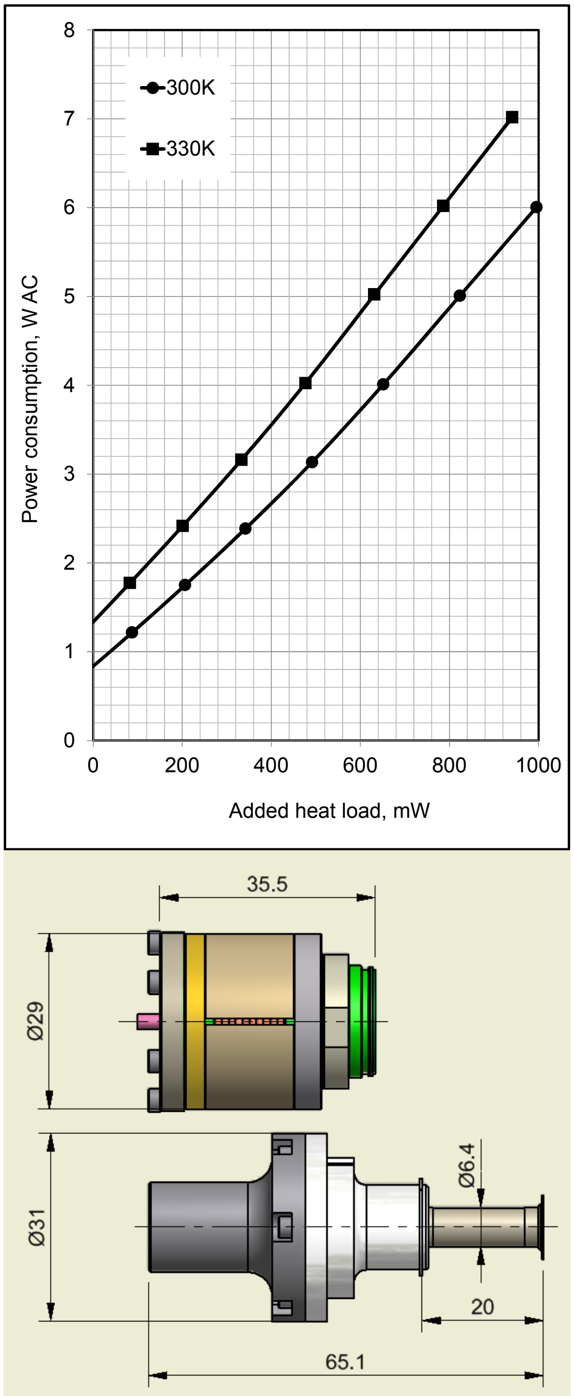


Figure 8. Predicted load curves and preliminary design outline of the downscaled cryogenic cooler with shortened cold finger

7. Vibration export

Vibration export is one of the key parameters characterizing cryogenic coolers. The low frequency portion of the vibration export may cause excessive line of sight jitter, while its high frequency components may cause excessive microphonics and audible noise through excitation of the structural resonances in a typically thin-walled metal IR imager enclosure.

As compared to the rotary rivals, the linear cryocoolers are known to be relatively quiet and produce very little high frequency vibration export; this is, primarily, due to a simplified actuation concept resulting in a smooth, impact-free reciprocation of the moving assemblies.

Imbalanced reciprocation of the moving assemblies in compressor and expander units results in the low frequency vibration export, the instantaneous magnitude of which is the product of moving mass and instantaneous acceleration [12].

The moving components in a piston compressor unit are usually heavier and associated strokes are larger than those in the expander. That is why the single-piston compressor is considered to be the major source of unacceptably high vibration export. In a dual-piston compressor – featuring two oppositely reciprocating piston compressors sharing a common compression chamber and driving current – essential momentum cancellation at fundamental frequency takes place. Therefore, it is widely accepted throughout the industry that a dual-piston compressor approach is the universal recipe for addressing the vibration export issue. The residual vibration export, however, cannot be absolutely nullified since it may be a function of asymmetry in friction factors, clearance seals and linear actuator performances. Typical magnitudes of vibration export at the driving frequency produced by dual-piston compressors, as reported by the major vendors of tactical coolers, are ranging from 1.5 to 2. N rms [12]. It is important to note that these figures might be time-dependent and with time may depart essentially from their initial values.

The known drawbacks of a dual-piston approach to a compressor design, as compared with the single-piston concept, are increased size, weight, power consumption and manufacturing cost. Moreover, their downscaling is limited since each sub-compressor may reach a critically small size, thus requiring extreme precision and complicated manufacturing technology. Downscaling of a single piston compressor however, allows for keeping a small size at regular manufacturability, and, may result in such reduction of moving mass and strokes that the produced vibration export will be already tolerable by the typical hand held application.

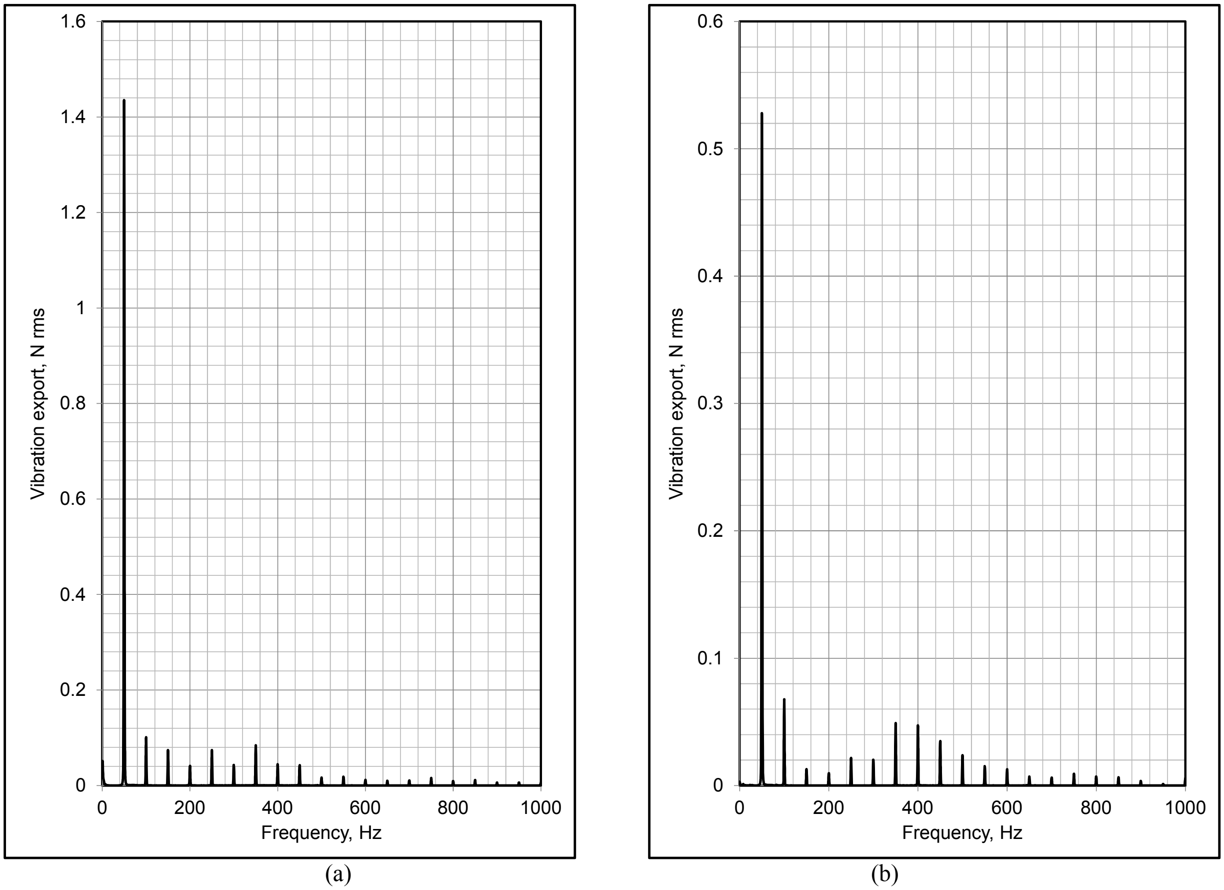


Figure 9. Predicted vibration export, (a) – compressor, (b) - expander

Figure 9 shows the predicted spectra of vibration export produced by compressor (a) and expander (b) units of the above mentioned cryocooler. The prediction relies on the measured vibration export produced by the standard K527 cooler working in a temperature regulation mode 100mW@150K@27°C. The data re-calculation accounted for the predicted (smaller) values of moving masses and strokes in compressor and expander units along with the lower driving frequency. From Figure 9, the vibration export produced by the compressor unit is similar to this produced by the typical dual-piston compressors. As to the vibration export produced by expander unit, it seems to be tolerable by the most demanding applications. In case of using such a cooler with extra-light imager, the authors are recommending to consider direct clamping of the compressor unit to the system enclosure and using light (say, 20gr) tuned dynamic absorber capable of, at least, 50-fold vibration suppression [12].

8. Controller options

It is obvious that forthcoming low power compact cryogenic cooler needs to be driven by a compact controller dissipating very little electrical power. The existing controllers are quite bulky and show insufficient performance when low heat lift is needed. Figure 10 shows the typical dependence of the coefficient of performance (COP) versus the power consumption shown by a regular controller of K527 cooler driven in 150K-temperature control mode. From Figure 11, at low cooling powers the controller COP is indeed unacceptably low. For example, at the working point 100mW@150K@27°C the power consumption is 1.6W and the parasitic heat dissipated by controller will be 0.5W. This may be explained by the high losses in the components of digital and protection circuitry, high frequency switching in power components, etc. The possible solutions may include removing not essential features, voltage and current protection circuitry, transferring digital control functions to the IR imager board, etc.

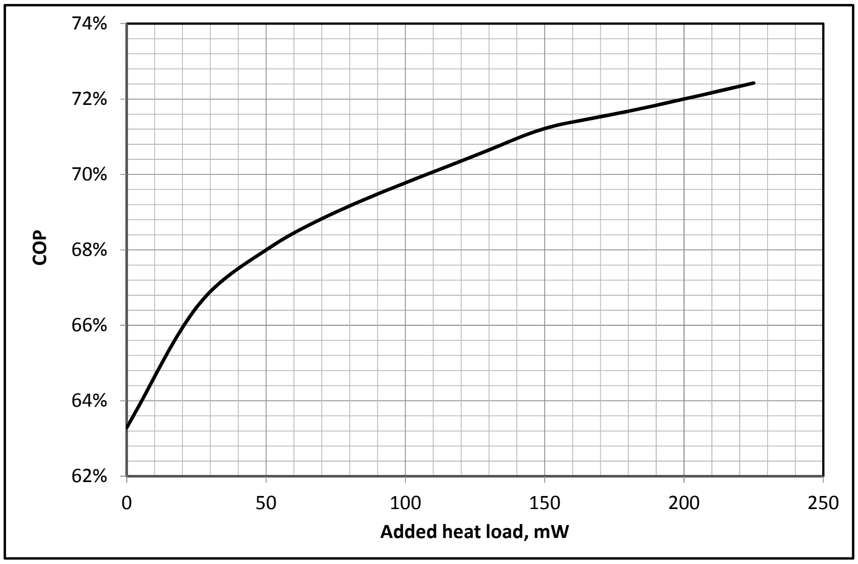


Figure 10. COP of the typical controller

Not less important will be removing the low frequency, typically active, filter from the electrical line connecting the DC power supply (battery, stabilized source, etc) and the controller input. This device is normally used to attenuate the double frequency voltage and current ripple occurring in the above line and capable of upsetting other electronic devices and controller itself. One of the possible solutions is the so called "constant current" driver, as explained in [13]. Additional advantage of such a driver is very high, in excess of 90%, and practically power-independent COP.

Summary

- Ricor K527 split linear Stirling cryocooler with regular and shortened cold fingers has been tested towards using with HOT (150K) infrared detectors.
- Experimental load curves were obtained; the numerical simulation software verified.
- From experiment, for the typical working point 100mW@150K@27°C the power consumption is 1.6W AC and 3 W AC for the regular and shortened cold fingers, respectively.
- The authors suggested thinning the cold finger walls to 0.05mm and using electro-polishing and gold plating of the evacuated envelope interior. The combined effect will be decreasing the Dewar self heatload by approximately 60mW@150K@27°C
- The authors conducted optimization and produced preliminary downscaled design of a split linear cryogenic cooler; the major design data is summarized below

Compressor dimensions, mm	Expander outline dimensions, mm	Cold finger OD/length, mm	Compressor/Expander weight, gr	Power consumption, 100mW@150K@27°C/57°C W AC
Ø29xL36	Ø31xL89.4	7.8/43	110/70	0.6/1.2
Ø29xL36	Ø31xL65.1	6.4/18	110/60	1.0/1.8

- The authors predict that the levels of vibration export produced by the downscaled compressor and expander will be below 2N rms at the driving frequency.

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