Linear Cryogenic Coolers for Hot Infrared Detectors

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ABSTRACT

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

Recent technological advances have allowed the development and fielding of high temperature infrared detectors working in the range 150-200 K while showing performance typical for their 77 K predecessors. The direct benefits of using such detectors are the lowering of the optical, cooling, and packaging constraints, resulting in more compact and cost effective optics, electronics and mechanical cryocooler.

The authors are formulating the requirements and a general vision for a prospective ultracompact, long life, lightweight, power efficient, acoustically and dynamically quiet, linear cryogenic cooler for forthcoming infrared imagers.

In particular, the authors reveal the outcome of a feasibility study and discuss downscaling options.

INTRODUCTION

Readiness of all-weather and night-fighting infrared (IR) 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 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 (77 K, 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. An additional preventing factor is awkward logistics of the supply and recharge of batteries.

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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 performance in both middle wavelengths (MW) and long wavelengths (LW) at an extremely low rate of defective pixels.

The 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.

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

Traditionally, integral rotary cryogenic coolers have been used for maintaining the 77 K focal plane arrays (FPA) of 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 the regulated temperature results in a drastic power draw reduction. Sofradir reported on testing their Scorpio detector integrated with a Thales RM2 integral rotary cooler [3]. In particular, for a standard Helium charge pressure and under standard environmental conditions, with a FPA temperature increase from 90 K to 150 K, the authors observed a 45% reduction in power consumption (from 4.0 to 2.2 W AC). Similar testing performed with Ricor's integral rotary cooler revealed in excess of 60% power draw reduction. This is largely explained by the 65% improvement of the Carnot coefficient of performance resulting from a 60 degree increase of the cold (acceptor) temperature (from 90 K to 150 K) 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, the compact double crank sliding linkage that features miniature ball bearings and is driven by a DC brushless motor has apparently exhausted its downscaling potential.

Further, at small heat lifts, the inherent parasitic losses appear to be comparable with the overall power consumption. These are: (i) friction in ball/needle bearings and in tight contact 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.

An additional known drawback of the above technology is the variable drive speed that is used for controlling the FPA temperature. As is known, both thermodynamic and electromechanic efficiency are strongly frequency-dependent and show well-distinguished optima at a particular operating frequency. The departure of the said frequency from its optimal value usually results in overall performance deterioration.

For the rotary integral cryocooler (Ricor model K561), Figure 1 shows typical dependencies of the **net** (AC) steady state power consumption on the added heat load at different stabilization temperatures (150 K and 170 K) and for the same +27°C reject temperature.

In Figure 1, both load curves show typical flat portions ranging from zero to 50 mW (150 K) and 100 mW (170 K), thus indicating the domination of parasitic losses over the useful "shaft power."

A further inherent known drawback of rotary integral technology is high vibration export resulting from the double-frequency oscillations of the driving torque and micro-impacts occurring in the clearances of the kinematic chain of the above double crank slide linkage.

Also typical are: high frequency noise, limited lifespan, and awkward packaging associated with fixed spatial orientation of compressor and expander portions of the cooler.

The above described limitations of the rotary integral technology have spurred the development of microminiature linear Stirling cryogenic coolers towards the long anticipated advent of HOT IR detectors.

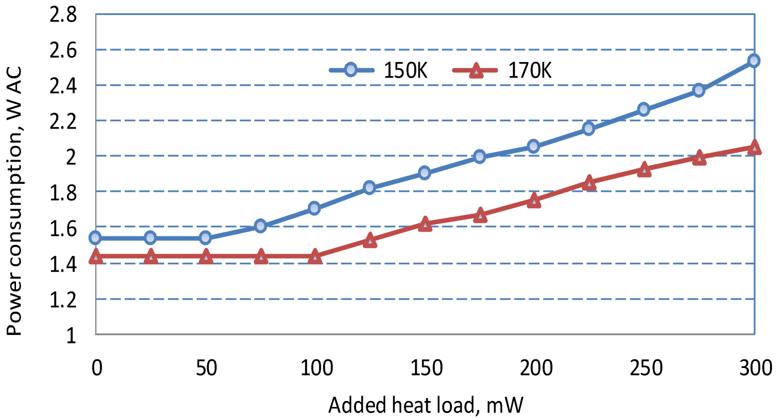

Figure 1. Typical load curves of rotary integral cooler.

The Ricor model K527 long-life, acoustically and dynamically quiet, split Stirling linear cooler was originally designed for 95 K FPAs [5-9]. This cooler features a resonantly "moving magnet" single-piston compressor and pneumatically driven resonant expander. It was the smallest in the split linear Stirling cooler market, and had superior performance indices [5-9]. It was also roughly comparable to the above mentioned rotary cryocoolers in terms of bulk, power consumption, and ownership costs.

AIM recently reported on their new cooler development for HOT detectors: a single piston, "moving magnet" split Stirling cryogenic cooler that is quite similar to the above mentioned K527 model in terms of mechanical design, size, weight, performance, and approach to attenuation of vibration export [10].

Known advantages of the linear technology, as compared with the rotary, are as follows:

Reduced Friction Losses in Compressor and Expander

Both compressor and expander units are driven linearly, using electro-dynamic and pneumatic actuation, respectively. There is no need, therefore, to transform rotary into linear motion. This eliminates a fundamental portion of the parasitic mechanical losses typical for the rotary technology that relies 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 armature iron and contains no parasitic lobe portions that are typical for rotary DC brushless motors, as normally used in integral rotary coolers. This results in the driver having inherently higher electro-mechanical 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 accordance with the required heat lift. This allows maintaining the optimal working conditions for all times. An additional favorable factor is that the performance of the linear electro-dynamic actuator may be optimized towards a single chosen driving frequency.

Improved Life Expectancy

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

Flexibility in IR Imager Packaging and Heatsinking.

A 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 of a linear cooler, the vibration export does not contain higher order harmonics and normally does not result is structural noise. From experience, the noise produced by an IR imager containing a linear cryocooler (2 meters measurement distance) is comparable with the background noise in a 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 yields an inherent mechanical simplicity and better potential for downscaling as compared with the rotary technology.

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

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 80 K@23°C indicates that this cooler is the smallest, lightest and most efficient over the range of “3/4 watt” linear coolers.

Because of the tight constraints imposed primarily on weight, price and cooling performance, 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 (0.035 kg) “magnet–piston” assembly guided by a precision 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 contact, tightly matched (4 μm radial gap) clearance seals made of the above tribological, wear-resistant material. Machined springs were used to minimize fretting-induced debris generation, side forces, and resulting seal wear. The feasibility of this approach was proven recently in the course of an accelerated life test (including temperature extremes) [12], 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.

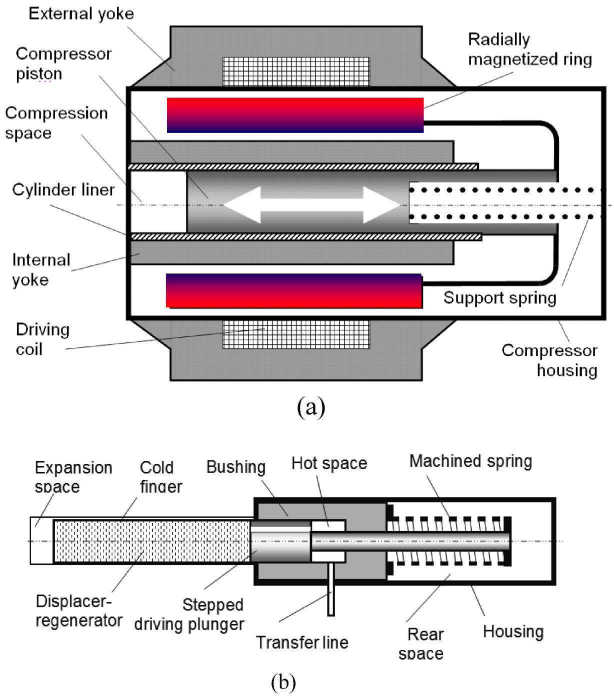

Figure 2. Schematic of a single-piston "moving magnet" linear compressor (a) and pneumatically driven expander (b).

Figure 2a shows a schematic of the 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 a 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 the 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.

Figure 2b shows a schematic 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 is centered and has the desired resonant properties.

Figure 3 shows an external layout and pictures of the linear compressor with both regular and shortened cold finger. The "Shorty" configuration was originally designed for a compact gyrostabilized IR application relying on HOT (130 K) detectors [6]. It features a cold finger which has been shortened from 43mm to 19mm.

Performance mapping of the K527 cryogenic cooler including regular and short cold finger working in a temperature control mode at 150 K has been performed at normal ambient temperature (+23°C) where the typical reject temperature is +27°C. The self heatload of the typical simulation dewars are approximately 105 mW@150 K@27°C and 190 mW@150 K@27°C, for the regular and

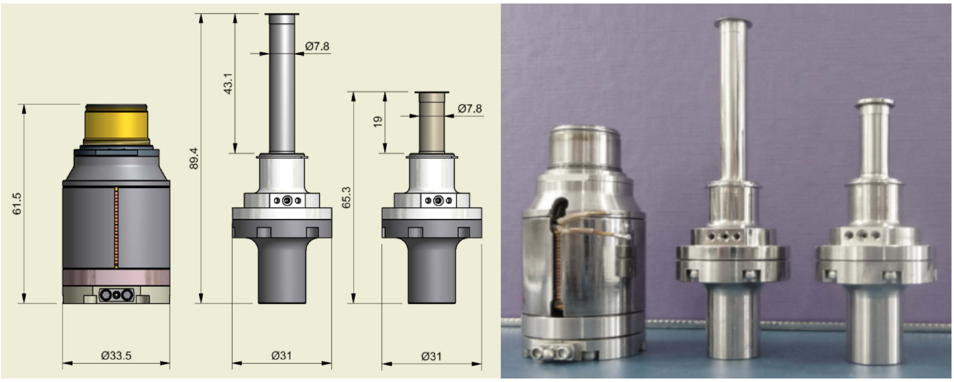

Figure 3. External layout and pictures of the linear K527 compressor, regular and shortened cold fingers.

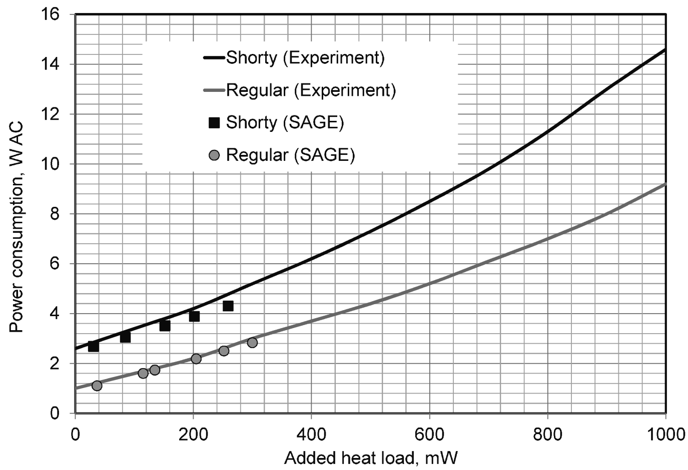

Figure 4. Load curves for the K527 cryocooler with regular and shortened cold fingers.

shortened cold fingers, respectively. Both coolers were loaded by a typical thermal mass 180 J@150 K➔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 dependency of the power draw on added heat load for loads ranging from 0 to 1000 mW (load curves). Data are provided for both the regular and "Shorty" K527 cooler working at the above described conditions.

Figure 5 shows typical dependencies of the FPA temperature and power consumption during the cooldown phase. From Figure 5a (case of regular cold finger), the cooldown takes 125 s, and the maximum power draw following the end of the soft start is 18.5W AC. From Figure 5b, (case of shortened cold finger), the cooldown takes 30 s, and the maximum power draw following the end of the soft start is 20.5W AC.

SAGE OPTIMIZATION FOR 150 K

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

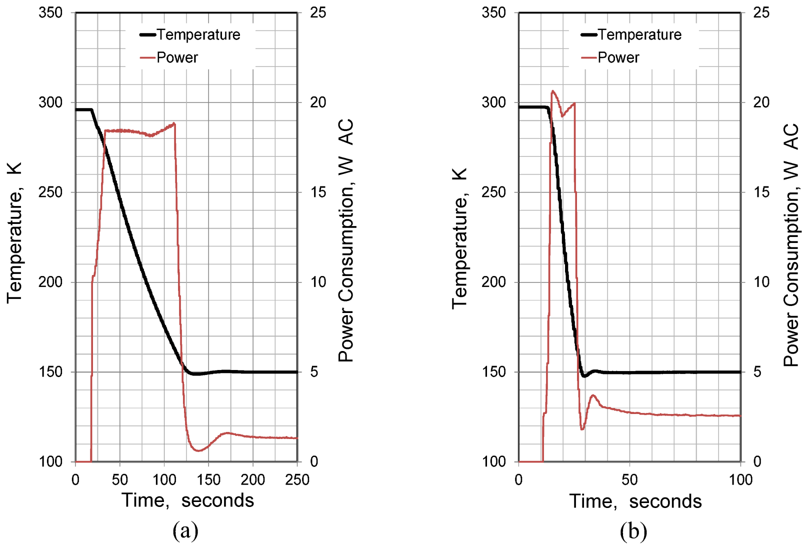

Figure 5. Cooldown curves for (a) regular and (b) shortened cold finger.

Prior to modifying the cooler for the new 150 K 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; these are normally operated in very mild environmental conditions, literally free of shock and vibration. 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 20 mW@150 K@27°C and 34 mW@150 K@27°C for the regular and shortened cold finger, respectively.

Further, electro polishing and gold plating the evacuated envelope interior can lower the emissivity factor down to 0.04 instead of a typical 0.2. This will reduce the radiation parasitic loads by approximately 40 mW@150 K@27°C and 28 mW@150 K@27°C for the regular and shortened cold fingers, respectively. The combined effect of thickening the cold finger wall and polishing/gold plating of the dewar interior produces approximately 60 mW@ 150 K@27°C of heat load reduction for both the regular and shortened cold fingers.

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

The optimization goal was to minimize the power consumption at the above working point (100 mW@150 K@27°C), by varying the regenerator material and porosity, charge pressure, and drive frequency. In all simulations we also assumed that the cold finger is made of L605 alloy with a wall thickness of 0.05mm; the emissivity of the dewar interior walls was assumed to be 0.04.

Figure 6a shows the 150 K load curves predicted by the SAGE simulation software for the optimized cooler featuring the regular 45 mm cold finger. Data for two different reject temperatures are presented, namely: 27°C (300 K) and 57°C (330 K), typical for the working range of hand held IR imagers. From Figure 6a, 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 1000 mW heat lift with a power consumption below 4 W AC.

Figure 6b also shows the initial design layout of the expander and compressor units. From models, the compressor and expander weights are 110 gr and 30 gr, respectively. Further mass and size reduction will be possible as a result of transitioning to an all-welded approach; the detailed discussion of this is beyond the scope of this paper.

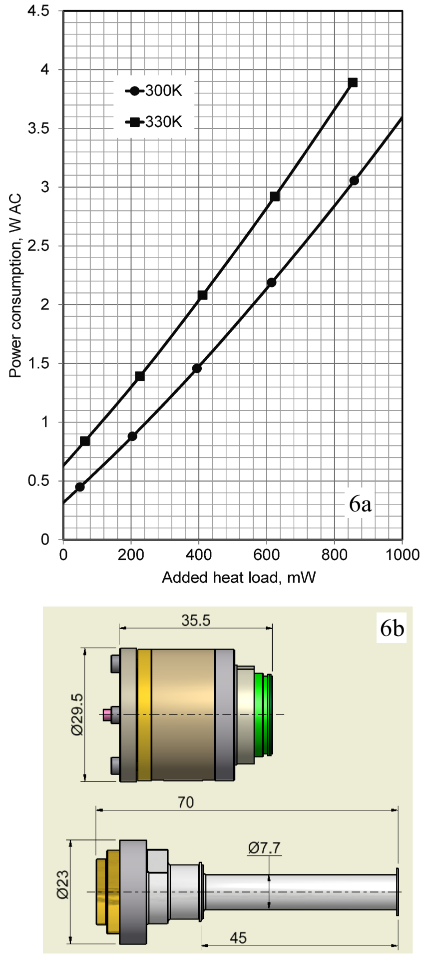

Figure 6. Predicted load curves and preliminary design outline of the downscaled cryogenic cooler with regular cold finger.

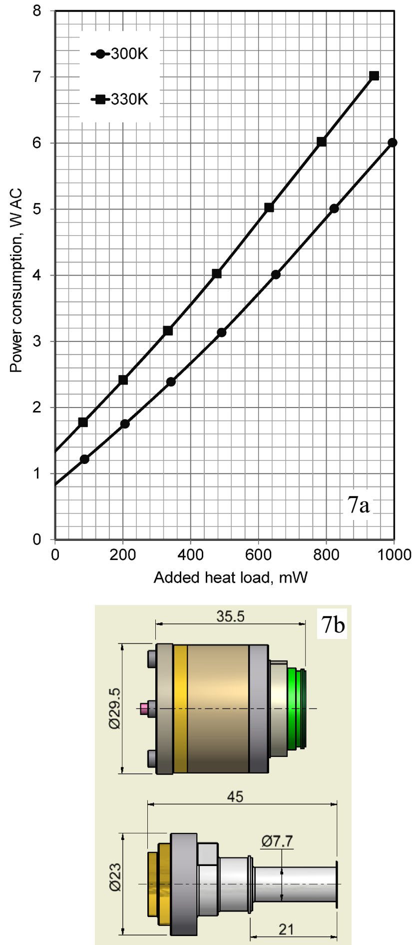

Figure 7. Predicted load curves and preliminary design outline of the downscaled cryogenic cooler with shortened cold finger.

As an additional activity, we also attempted to optimize the cryogenic cooler featuring the shortened 20 mm expander. Here, the ultimate optimization goal was again to minimize the power consumption at the above working point (100 mW@150 K@27°C), by varying the cold finger ID, regenerator material and porosity, piston OD, charge pressure, and drive frequency.

Figure 7a shows the 150 K 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 (300 K) and 57°C (330 K). From Figure 7a, the power needed at the specified working point 100 mW@150 K@27°C will be as low as 1.2 W AC; the power consumption will rise to 1.8 W AC at 57°C (330 K). It is important to notice that the obtained cooler is capable of delivering up to 1000 mW heat lift with power consumption below 7W AC. Figure 7b shows the initial design of the expander and compressor units.

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 fre-

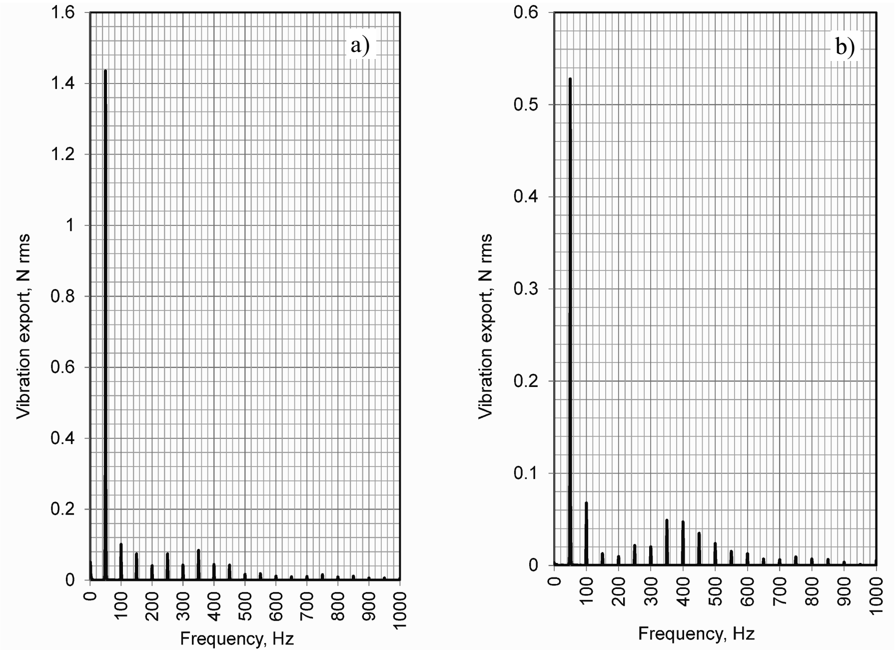

Figure 8. Predicted vibration export of a) compressor, and b) expander.

quency content 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 their rotary rivals, linear cryocoolers are known to be relatively quiet and produce very little high frequency vibration export; this is primarily due to their simplified linear actuation concept that results 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 the 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 performance. Typical magnitudes of vibration export at the driving frequency produced by dual-piston compressors, as reported by the major vendors of tactical coolers, range from 1.5 to 2.0 N rms [13].

It is important to note that these figures might be time-dependent and with time may depart significantly 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 8 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 actual vibration export produced by the standard K527 cooler and accounts for the smaller moving masses and strokes in compressor and expander units along with the lower driving frequency.

From Figure 8, the vibration export produced by the compressor unit is similar to that produced by typical dual-piston compressors. As to the vibration export produced by the 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 recommend that one consider directly clamping the compressor unit to the system enclosure and using a light (say, 20 gr) tuned dynamic absorber capable of, at least, 50-fold vibration suppression [13].

SUMMARY

- A Ricor K527 cryocooler with regular and shortened cold fingers was tested at 150 K. Experimental load curves were obtained; the numerical simulation software was verified.
- For the typical working point (100 mW@150 K@27°C) the power consumption is 1.6 W AC and 3 W AC for the regular and shortened cold fingers, respectively.
- It was shown that the dewar heat load could be reduced by 60 mW@150 K@27°C by thinning the cold finger walls and electro-polishing/gold plating of the evacuated envelope interior.
- The authors conducted optimization and produced a preliminary downscaled design of a split Stirling linear cryogenic cooler

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