Status of AIM Space Cryocoolers

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ABSTRACT

The growing market of commercial space applications and satellite programs has significantly increased the demand for infrared detectors. High performance Infrared (IR) detector systems are mostly equipped with Stirling or pulse tube coolers to provide sufficient cryogenic cooling for maximum electro-optical performance. The focus for these cryocoolers is on reliability and life time, thermal performance, and also on cost. To fulfill these demands AIM has focused on Integrated Detector Cooler Assemblies (IDCA) with long life cryocoolers similar to those being used for tactical applications.

Design of this cooler family is based on all-welded compressors featuring flexure bearing and moving magnet technology with customer-specific thermo-mechanical and electrical interfaces. In distinction to most of the tactical applications, a pulse tube is used instead of a Stirling coldfinger.

Some years ago, AIM delivered a MW-IR-IDCA with a SF400 pulse tube cooler for a Korean Space program. This unit was launched in March 2015 and is the first European pulse tube cooler in space.

An overview of ongoing AIM space cryocooler development activities is presented. This includes the latest cooling performance maps, environmental tests, and life test results of the SF-cooler family. The status of life time testing with > 65,000 real-time hours at elevated temperature and high power operation is also presented.

The reliability of an overall system can be increased by incorporating redundant cryocoolers. For a standard, compact IDCA a fully redundant cooling system cannot be achieved. Therefore a switching valve has been developed to allow operation of one pulse tube from a redundant pair of compressors. This activity was supported by the German DLR Space Agency in a study "Reliability and redundancy concepts for space cryocoolers used in IDCA solutions." The improvement of this valve is the topic of phase II. The valve was optimized in regard to its reliability and lifetime. An overview of these activities is also presented.

INTRODUCTION

AIM started the development of a long-life cooler with flexure bearing and moving magnet technology several years ago [2, 3]. The main focus during this development was to improve the lifetime of tactical coolers. Additionally, AIM developed a pulse tube cooler in cooperation with the University of Giessen [4, 5]. When AIM, also an IR system manufacturer, started with the development of infrared detector systems for low Earth orbit operation, it was decided to build up Integrated Detector Cooler Assemblies (IDCA). Thus, a space qualified cryocooler also was needed.

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Table 1. Comparison of standard linear (moving coil) and flexure bearing (moving magnet) compressor design.

Category	Percentage change of SF design based on SL compressor
Number of parts	-56 %
Thread joints	-71 %
Glued joints	-60 %
Welded joints	+275 %
Materials with potential for outgassing into Helium vessel	**-97 %**

To fulfill typical space mission requirements in terms of reliability, mechanical robustness, and irradiation hardness, the AIM developed pulse tube space cryocoolers with flexure bearing moving magnet compressor technology based on a tactical long life cooler with the same basic design. AIMs Long Wave Infrared (LW-IR) detector system is based on the SF400 flexure bearing compressor. For a Short Wave Infrared (SW-IR) detector system AIM has chosen the smaller SF100 compressor.

To fulfill typical space mission requirements in terms of reliability, mechanical robustness, and irradiation hardness, a radiation hardened, redundant cooler electronics had to be developed.

The following sections give an overview of the design of our cooling system and the environmental qualification of both cooling systems and the cooler electronics.

TACTICAL LONG-LIFE COOLER DESIGN

Design of Flexure Bearing Moving Magnet Compressors

More than ten years ago, AIM started its activities to develop long life coolers. The MTTF of a standard linear cooler (SL-Design) was around 10,000 hours at that time. The main lifetime limiting factor for these coolers was the contamination of the working gas, primarily caused by the coil inside the vacuum vessel. Also the wearout mechanism of the piston coating and of the Stirling expander contributed to a limited life of the cryocooler.

For the design of a long life cooler the desire was to entirely eliminate these mechanisms. Thus, AIM decided to develop a new compressor of a moving magnet flexure bearing design. The moving magnet design allows the positioning of the coils outside the helium vessel. Beside the removal of this contamination source, there is no need for an electrical feedthrough, a source for statistical failures. The elimination of a flying wire further helps to decrease the statistical failure rate.

To reduce the amount of organic material inside the compressor to a minimum it was necessary to change the connection technology. Minimum use of glued and threaded joints helps to minimize the contamination potential. Table 1 shows a comparison of the standard linear (moving coil) and the flexure bearing moving magnet design.

In order to prevent abrasion of the piston coating, the long life cooler series uses flexure bearing technology with clearance seals. The idea is to centre the piston within its sleeve to eliminate contact and wearout. Of course, this is not an easy task considering a nominal piston gap of only a few microns. To realize this concept it was necessary to develop a computerized alignment system with sufficient accuracy.

Design of Pulse Tube Coldfinger

One key requirement for the development of a long-life tactical cooler was the desire for a form fit function replacement of a standard linear Stirling cooler. For the coldfinger, a compatibility to the

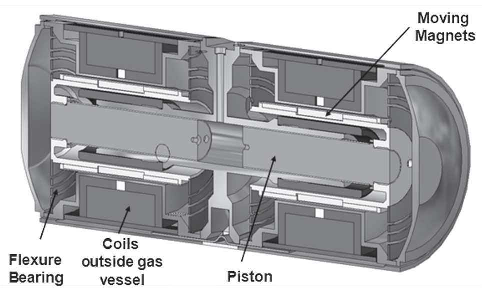

Figure 1. Principle design of AIM flexure bearing moving magnet compressors [2].

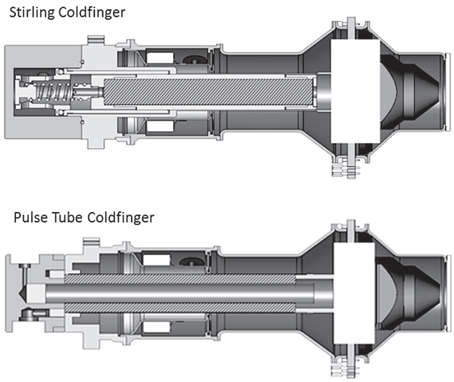

Figure 2. Comparison of AIM Stirling coldfinger and pulse tube coldfinger in AIM standard ½" dewar.

AIM standard ½" dewar was required. For the long-life cooler, a redesign of the Stirling coldfinger was reasonable. The use of high performance plastics reduced the wear and tear. The careful selection of construction materials and connection technologies led to a lifetime in the range of 20,000 to 30,000 hours.

For an ultra-long life cooler, the use of a pulse-tube coldfinger is necessary. In cooperation with the University of Gießen, AIM developed a compact coaxial pulse tube coldfinger that fully fits into the AIM standard ½" dewar. Without any organic materials or moving parts, the pulse-tube coldfinger is designed for lifetimes above 60,000 h. So far, no life limiting effect is known or observed for such pulse tube coldfingers.

SPACE SPECIFIC DESIGN

Once a cryocooler has the capability to meet the lifetime requirement of a space mission, the main difference between a tactical and a space cooler is its interfaces. For a tactical cooler, besides the mechanical clamping, an additional interface to mount a fan is a common approach. For low power applications sometimes just the mechanical interface is used for heat removal. However, space coolers typically need a suitable interface for the mounting of a thermal link or a heat pipe, and in addition, there are specific requirements for the mechanical interface. Depending on the thermal management concept, conductive cooling through this mechanical interface may not be desired.

For different space programs AIM has developed, in close collaboration with the customer, a reasonable thermal and mechanical interface. Figure 3 shows a comparison between two space pulse-tube coldfingers. They are based on the same thermodynamic design of the coldfinger. The difference is just the thermo-mechanical interfaces. The thermal interfaces are matched to the program-specific heat pipes. The dewar flange is adapted to the outer dewar used in the particular program.

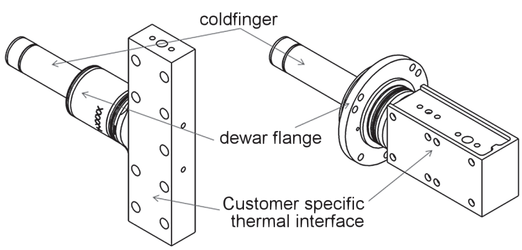

Figure 3. Thermal and mechanical interface of pulse tube coldfinger for different applications.

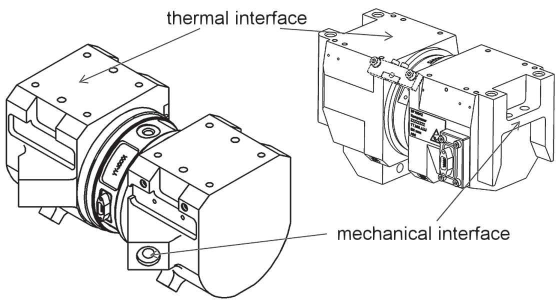

Figure 4. Thermal and mechanical interface of SF400 for a Korean space program (left) and SF100 for a German space program (right).

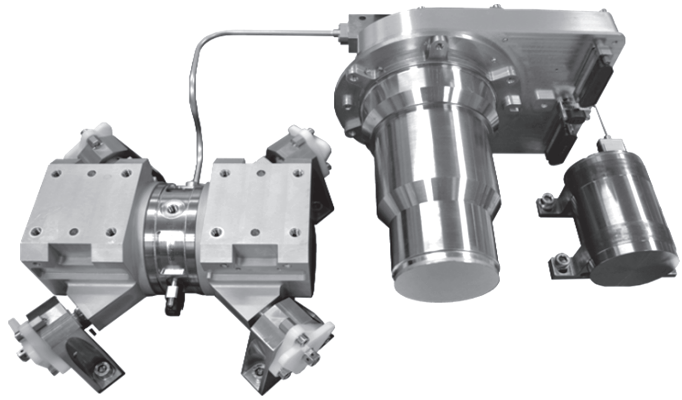

Figure 5. AIM MWIR detector with SF400 flexure bearing compressor + ½“ pulse tube cold finger.

The interfaces of the compressor are matched to the requirements of its corresponding program. While clamping of the compressor is standard for tactical cryocoolers, space coolers need a more specific mechanical interface. Also, the thermal interface is more demanding due to the vacuum in space. To benefit from the maturity of tactical coolers, only the outer housing was changed to provide reasonable space interfaces. Figure 4 shows the thermal and mechanical interfaces of the SF400 and the SF100 in their space version.

KOREAN SPACE PROGRAM

Some years ago AIM delivered the flight model of an integrated detector cooler assembly for a Korean space program (see Figure 5). Due to the huge size of the detector and cold shield of this mid wave detector system, the SF400 flexure bearing compressor was chosen to provide enough performance margin. The cooler was optimized for an operating temperature of 80 K and includes the adapted interfaces outlined above. The total weight of the mechanical cryocooler is 4.70 kg. The cooler system was delivered with a fully redundant cooler control electronics (Figure 6) with an additional weight of 3.44 kg.

The cryocooler and the cooler control electronics have been qualified as part of the IDCA qualification program. Details of the qualification and also performance data of the cooling system can be found in [1]. A picture taken from the Korean satellite, which was launched in March 2015, is shown in Figure 7.

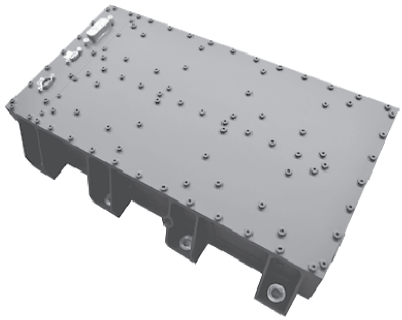

Figure 6. AIM cooler drive electronics (fully redundant)

Figure 7. Picture of Soul taken from Korean satellite (Source: KARI)

GERMAN HYPERSPECTRAL IMAGING INSTRUMENT

For this instrument a short wave infrared detector will be used. Because of the wave length of the detector, the operating temperature of the cooler is significantly higher than the operating temperature of the mid wave system. The cooler for this system is optimized for operation at 150 K. Due to the lower input power needed for cooling in this temperature range, AIM selected the smaller SF100 compressor for this application. Figure 8 shows the SF100 cooler integrated into the IDCA mounted on a transportation plate.

With the customer-specific interfaces, the total weight of the mechanical cryocooler is 3.00 kg. The cooler control electronics are based on the electronics used for the Korean program. Due to customer requirements, an additional Tele-measurement and command capability was implemented. Including these additional capabilities, the weight of the electronics is still below 3.50 kg.

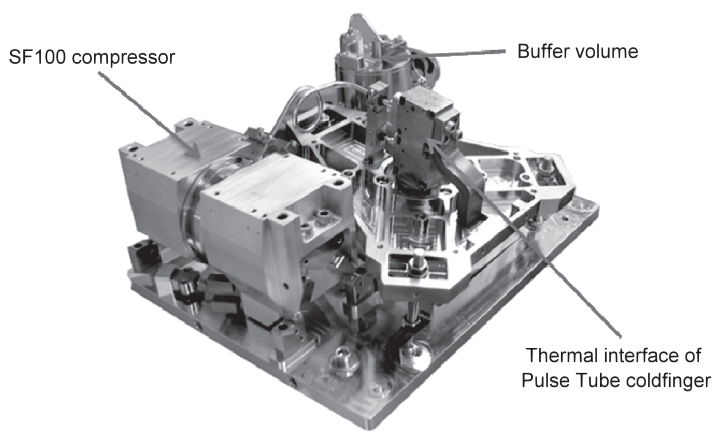

Figure 8. AIM SWIR detector with SF100 flexure bearing compressor with ½" pulse tube cold finger

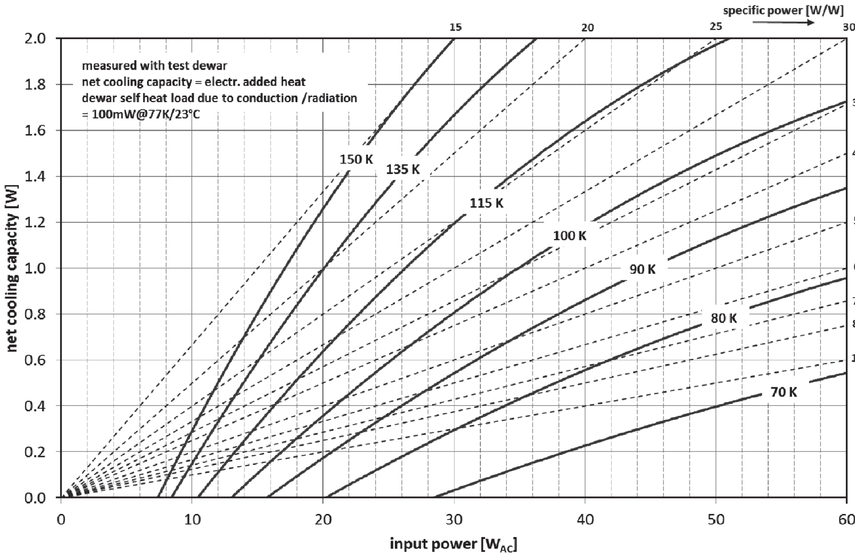

Figure 9. Performance data for the SF100 pulse tube cooler.

On a cooler level, the SF100 has passed launch vibration and thermal vacuum pretests. The final qualification of the cooler will be performed at the IDCA level. The QM of the IDCA is currently being built up. The launch for this system is scheduled for 2018. Figure 9 shows the thermal performance data.

COOLING SYSTEM LIFE TIME VERIFICATION

Long lifetime is one of the main requirements of a space cooler. Thus, lifetime tests are mandatory. As part of system qualification AIM performs lifetime tests for different coolers. All coolers operate in open-loop-mode with a fixed input power of at least 80% of the rated power. Thus, the input power is 1.5 to three times higher than the steady state power predicted for nominal operating conditions. The heat removal is realized by natural convection only. Thermal interface temperatures are on the order of 50°C, and thus roughly 25 K above the nominal reject temperature at the system level.

Cooling performance and helium leakage tests are performed on a regular basis to check performance and life time stability. In addition, high temperature operating cycles are being performed regularly. Figure 10 shows, by way of example, the lifetime test of the SF400 cooler in bench-top operation.

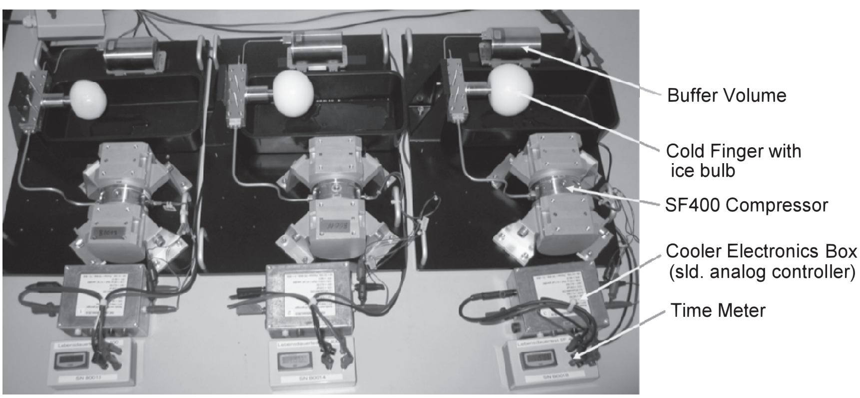

Figure 10. On-bench lifetime test of SF400.

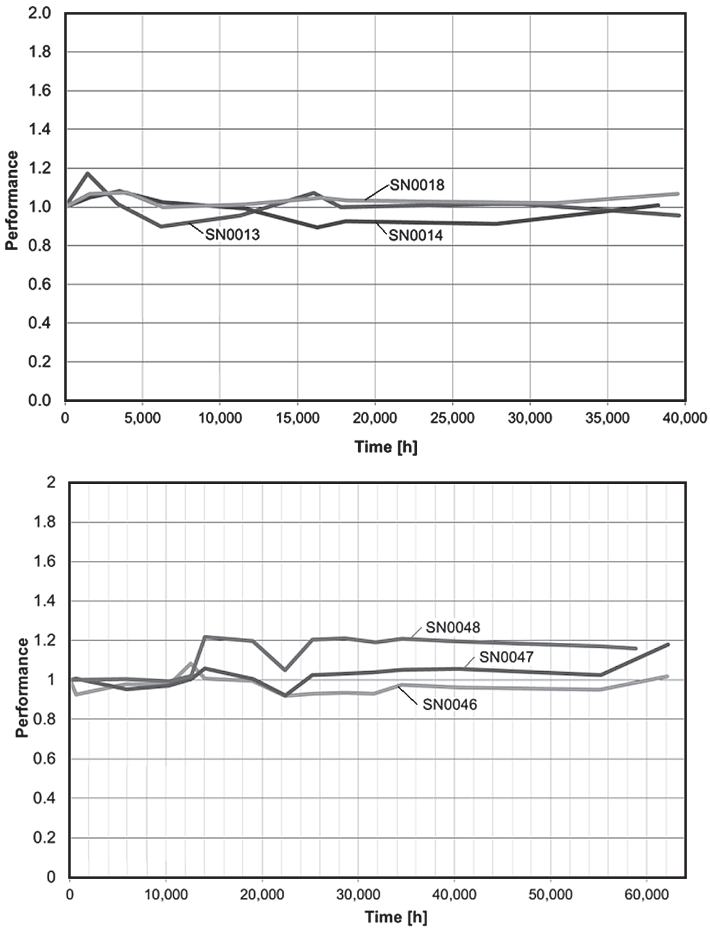

Figure 11. Relative performance over lifetime of SF400 (top) and SF100 (bottom), both with pulse tube coldfinger.

The relative performance of SF100 and SF400 over lifetime is shown in Figure 11. Relative performance is the ratio of cooling capacity divided by cooling capacity at the start of lifetime test for the nominal operating point. Deviations can be attributed to changing measurement equipment over time. First of all the integration into the measurement dewar and the calibration of the copper thermal mass results in variations. Table 2 shows the status of coolers in test with achieved life time operating hours to date.

Table 2. Status Lifetime test of AIM Long-Life cooler (May 2016).

Compressor type	Coldfinger type	No. of coolers	Operating hours	Status
SF070	¼” Stirling	1	~63 700	Ongoing, minor performance degradation observed yet
SF070	¼” Stirling	3	~35 200	
SF100	13mm Sirling	2	~34 500	Stopped due to displacer wear out after 10% Performance degradation
SF100	½” Pulse Tube	3	~64 800	Ongoing, no performance degradation observed yet
SF400	½” Pulse Tube	3	~41 800	Ongoing, no performance degradation observed yet

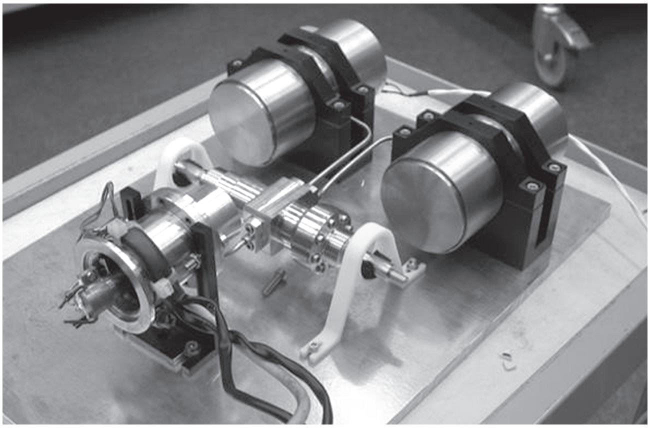

Figure 12. AIM pulse tube cooler with redundant compressors connected via switching valve.

FURTHER ACTIVITIES

Compressor Redundancy

As described above, reliability is the predominant requirement for space cryocoolers. Even for cryocoolers being designed to achieve lifetimes in excess of the mission life, single failures may lead to an early failure of the instrument. A common way to increase the reliability of space systems is redundancy, which is mainly used for cooler drive electronics. But for integrated detector cooler assemblies cooler redundancy is very demanding. Integrating a second pulse tube in the dewar will result in loss of some of the key advantages that are attractive for this IDCA approach, namely compactness, thermal efficiency, and usage of standard proven parts. In the scope of a DLR funded project, AIM investigated redundancy concepts for IDCA systems.

Advantages and disadvantages of various systems have been analyzed and assessed in detail. Due to the fact that the pulse tube has a very low statistical failure rate and no known ageing phenomena, use of only a redundant compressor was judged as a viable solution.

To realize compressor redundancy, an additional switching valve is required. There are a lot of requirements that need to be fulfilled by this valve. It has to have a very low leakage rate, internal as well as external. Internal leakage between the two compressors would increase the power consumption of the cooler. An external leakage rate would decrease the lifetime of the cooling system due to loss of the working gas. Also, organic materials would decrease the lifetime due to contamination of the working gas.

The development of a demonstrator of a suitable switching valve was part of the first study (Fig. 12). Analysis of weak points and optimization of the demonstrator was part of a second study, also funded by the DLR.

Performance Optimization

Besides reliability, the performance of space cryocoolers is one of the main requirements. Higher efficiency decreases the power consumption and thus also the heat to be removed by a radiator.

During development of the AIM pulse tube, a main requirement was to fit into the AIM standard dewar. If this requirement were given up, a considerable performance improvement would be possible. Simulations done so far predict an increase in efficiency of about 25%. With the lower PV-power needed with this 25% improvement, it would be possible to substitute a smaller compressor for the same application. The SF100 compressor would be able to provide sufficient cooling for midwave IR applications down to 80 K. The SF400 compressor even becomes a suitable solution for application down to 65 K. Besides decreasing the power consumption of the cryocooler system, the weight of the cooling system can also be reduced.

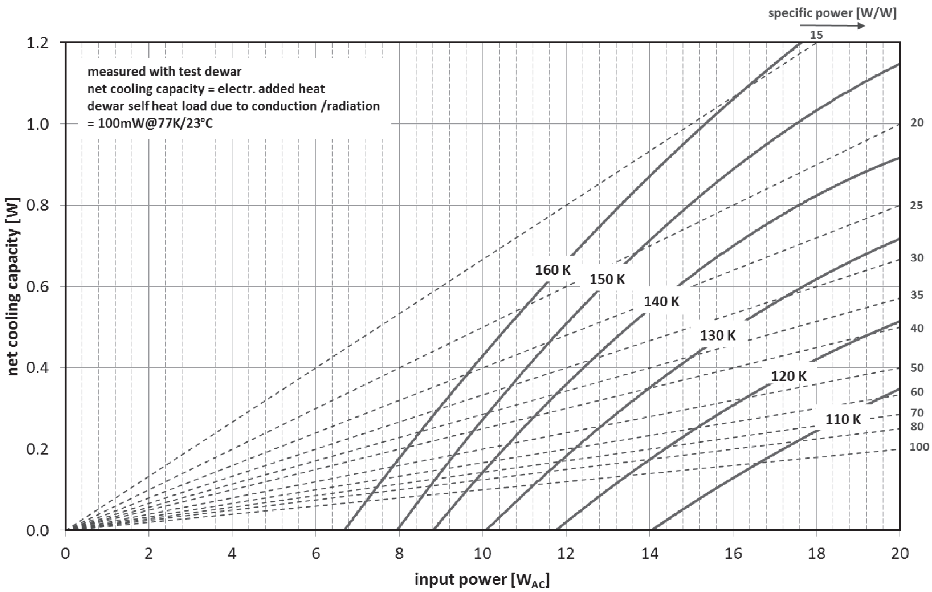

Figure 13. Performance data of SF070 with AIM pulse tube coldfinger.

Pulse Tube Cooler with SF070

Within the last decade there have been numerous activities to increase the operating temperature of infrared detectors. In the past, for example, a standard mid-wave detector operated at about 80 K. A state-of-the-art High Operating Temperature (HOT) mid-wave IR detector now allows operation at 140 K and above. With increased operating temperature the needed PV-power and thus compressor size can be decreased.

Several years ago, AIM developed the SF070 [2], based on the same technologies (moving magnet, flexure bearing) like the SF100 and the SF400. This compressor also can be used to provide the necessary PV-power for the AIM pulse tube coldfinger. Figure 13 shows a performance mapping for this cooler. For use as a space cooler, the thermal and mechanical interfaces need to be adapted.

SUMMARY AND CONCLUSIONS

In recent years, AIM has been involved in several space cryogenics applications. Space cryocoolers for different programs have been developed. A MW-IR-IDCA with AIM space cryocooler was successfully qualified, delivered, and launched in 2015. The qualification model of a SWIR-IDCA, also utilizing an AIM space cryocooler, is currently being assembled. Launch for this module is scheduled for 2018. Additionally, AIM has developed a switching valve for space cryocoolers. This valve allows a redundant compressor to be incorporated within an IDCA system.

Further activities are related to improvement of efficiency and reduction of weight. Simulations predict improvements in efficiency on the order of 25% by optimization of the pulse tube coldfinger. This also allows switching to a smaller compressor for the same cooling capacity due to the less PV-power needed.

Performance mapping of the SF070 compressor with the same AIM pulse tube coldfinger demonstrated that this is also a viable solution to provide sufficient PV-power for the AIM pulse tube coldfinger. Using the same technologies as the SF100 and SF400 coolers, this cooler can also meet typical requirements of space missions.

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