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Performance and Reliability Characteristics of the Free Piston Free Displacer Stirling Cryocooler

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Abstract-- **This paper presents the results of a series of performance and reliability tests for the Stirling cryocooler. Infrared sensor systems incorporating cryocoolers are required to be qualified to the appropriate specification for the performance and reliability. FPFD Stirling cryocooler is currently under development for cooling infrared detector. Manufactured Stirling cryocooler delivers approximately 0.9W cooling at 80K for 30W ~ 40W of input power. It takes approximately 2 minutes to cool down to 80K at the ambient temperature of 23℃. Performance characteristics for the vibration, acoustic noise, EMI and leak rate of the Stirling cryocooler are evaluated. We performed low and high temperature keeping test from -32℃ to +52℃ and operating test at high and low temperature cyclic range with acceptance tests performed at scheduled intervals. Cooling capacity is determined as a function of the temperatures at the compressor, hot end and cold tip at the expander. Finally, we describe the experimental facility for the MTTF evaluation and some typical results of the Stirling cryocooler.**

1. INTRODUCTION

Over the past decade and a half there has been rapid development of Stirling cryocoolers, mainly for military and space applications. The cryocoolers working on the Stirling cycle are characterized by high efficiency, fast cool down, small size, lightweight, low power consumption and high reliability [1]. Stirling cryocoolers have been widely used for the cooling of infrared sensors and high temperature superconducting filters to 77K. Recently, the split-type Stirling cryocoolers driven by linear compressors have been used to fit the requirements of a long operating life [2, 3, 4].

The FPFD(Free Piston Free Displacer) Stirling cryocooler consists of two compressor pistons driven by linear motors, which make pressure waves, and a pneumatically driven displacer piston with regenerator. In general, efficiency of the Stirling cryocooler is mainly affected by the efficiency of the linear motor, resonant frequency of the compressor and the expander, displacement of the piston and the displacer and phase shift between piston and displacer [5, 6, 7].

This paper presents the results of a series of performance and reliability tests for the Stirling cryocooler. Infrared sensor systems incorporating cryocoolers are required to be qualified to the appropriate specification for the performance and reliability.

2. EXPERIMENT DESCRIPTION

2.1. Design of the Stirling cryocooler

Fig. 1 shows the schematic view of the FPFD Stirling cryocooler. FPFD Stirling cryocooler consists of two major parts; linear compressor module and expander module. Linear compressor consists of linear motor, inner and outer yoke, permanent magnet, coil, cylinder, piston and spring. Expander module consists of displacer, regenerator in the displacer, displacer cylinder, spring and heat exchanger.

Major factors in design process to improve performance of FPFD Stirling cryocooler are permanent magnet, coil characteristics, materials of yokes and magnet, and in operating process are charging pressure, volume of the split tube and operating frequency.

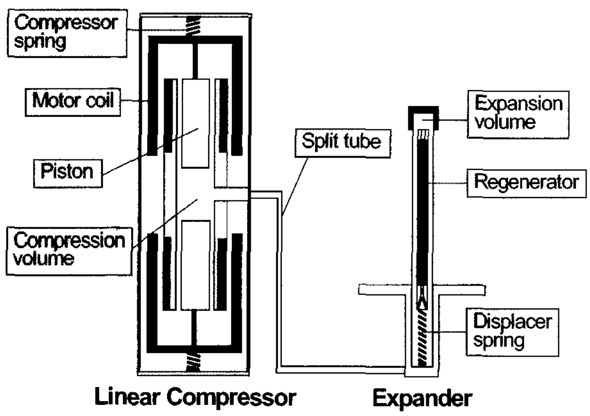


Fig. 1. Schematic diagram of the FPFD Stirling cryocooler.

Table 1 shows the main specifications of the FPFD Stirling cryocooler we have developed. Table 2 shows the favorable structure to satisfy specifications of the FPFD Stirling cryocooler. The reason why we have chosen a split type and also a type of a linear motor driven compressor is that this type of a cryocooler had been considered to be able to take a fully oil-less configuration and to fit the requirement of a long life.

Table 3 shows dimensions and materials of piston, displacer, regenerator and magnet in the Stirling cryocooler. Helium is used as the working fluid in the Stirling cryocooler cycle because of its ideal gas properties, its high thermal conductivity, and its high ratio of specific heats.

TABLE I.
Performance of FPFD Stirling cryocooler

Items	Specifications
Refrigerating cycle	Stirling cycle
Cooling power	0.5W at 77K
MTTF	5,000hours
COP	0.03
Cool-down time	5minutes
Configuration	Split linear

TABLE II.
Structure of Stirling cryocooler

Items	Requirements	Structure
Drive mechanism	Oil free	Free piston Free displacer
Motor	Controllability of frequency and force	Linear motor
Bearing	Low-contact High centering	Coil spring Fine gap seal
Control	Cooling power control	Displacement control

TABLE III.
Dimensions and materials of the FPFD Stirling cryocooler

Items	Materials	Dimensions (mm)
Piston	SUS 304	$\Phi 12 \times 20$
Displacer	SUS 304	$\Phi 5.8 \times 70$
Regenerator	SUS 304	ϕ 40μm × 89μm, # 250
Magnet	NdFeB	$\Phi 35 \times 20$

2.2. Performance test of the Stirling cryocooler [8]

Fig. 2 shows the schematic diagram of the performance and environmental test apparatus of the FPFD Stirling cryocooler. The most fundamental performance attribute of a cryocooler is its ability to cool a refrigeration load to a particular temperature. Refrigeration performance generally depends on a wide variety of performance variables such as cold-head temperature, expander heat-sink temperature, compressor heat sink temperature, compressor input power, compressor stroke, compressor drive frequency or speed (rpm), expander stroke and phase, and working-fluid fill pressure.

A load heater and a silicon-diode thermometer were attached to the cold head. A manganin resistance heater was provided at the cold end to measure the cooling capacity. After attaching them, the cold end of the Stirling cryocooler was inserted in the vacuum chamber for vacuum shield. A vacuum chamber was connected to the high vacuum pump under a pressure of 10^{-5} Torr during the experiment.

The high vacuum pump system consists of a rotary roughing pump, diffusion pump and vacuum gauges.

Fig. 3 shows Stirling cryocooler for performance and environmental test.

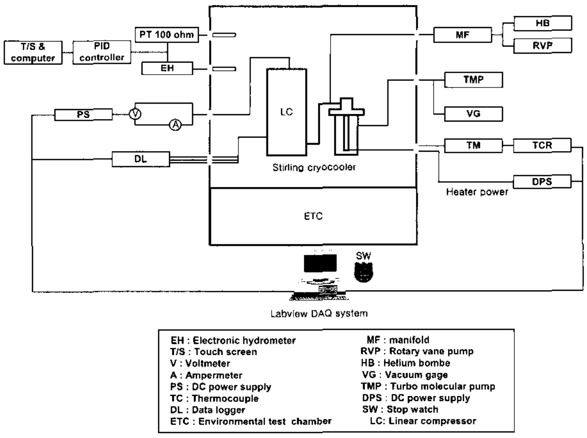


Fig. 2. Performance and environmental test apparatus.

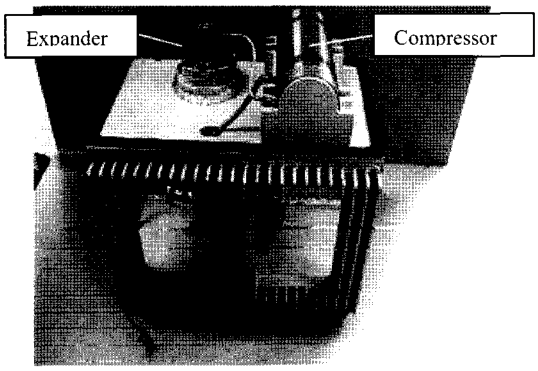


Fig. 3. Stirling cryocooler for performance and environmental test.

2.3. Reliability test of the Stirling cryocooler [9]

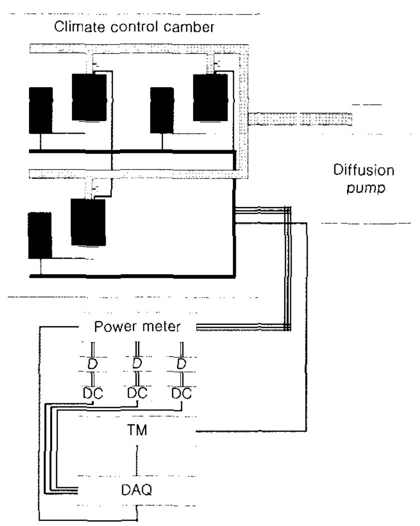
The needs for the cryocooler which has high reliability and long MTTF (Mean Time To Failure) are increased in the military and commercial thermal imaging system. The gas contamination, wear, leakage of working fluid, fatigue and etc. have the significant effects on the reliability and MTTF or MTBF(Mean Time Between Failure) of the Stirling cryocooler.

Fig. 4 shows the schematic diagram for reliability test and Fig. 5 shows the Stirling cryocooler for reliability Test. The room temperature test profile for the reliability cycle is described in Fig. 6. The cycle includes −32, +23 and +52 °C, with cooldown required at +23°C ambient. Three Stirling cryocooler are to be operated until:

- Failing to meet 90% of the cooling requirements (cooling capacity of 0.8W at 80K with the room temperature of +23°C)
- Failing to meet the cooldown requirement (cooldown time of 6minutes at the room temperature of +23°C)

- Failing to meet the leakage rate requirement (measured every 1000hours)
- Failing to meet the vibration output of requirement (measured every 1000hours)

The MTTF is to be determined as the average of the three results obtained.



D: In house motor driver DC: DC power supply
TM: Temperature monitor MON: Data logger
DAQ: Notebook PC(Labview DAQ system)

Fig. 4. Experimental apparatus for reliability test.

Fig. 5. Stirling cryocooler for reliability test.

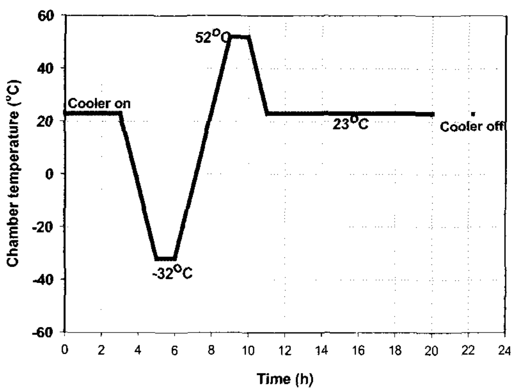


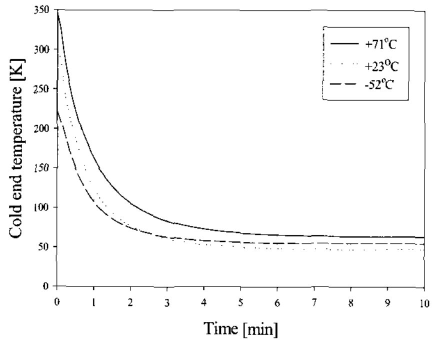
Fig. 6. Room temperature profile for reliability test

3. EXPERIMENT RESULTS

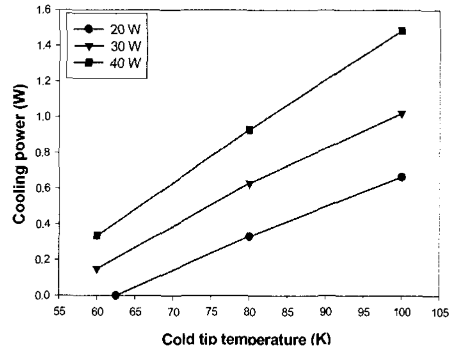
3.1. Performance test results

3.1.1. Cooling capacity, cooldown time and input power

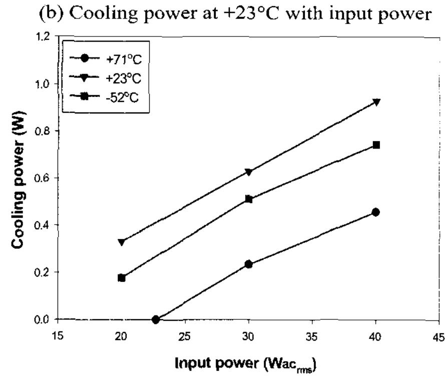
Fig. 7 shows the cooldown characteristics with ambient temperature (a), the cooling power at room temperature of +23°C with input power (b), the cooling power at 80K with ambient temperature and input power (c) and the



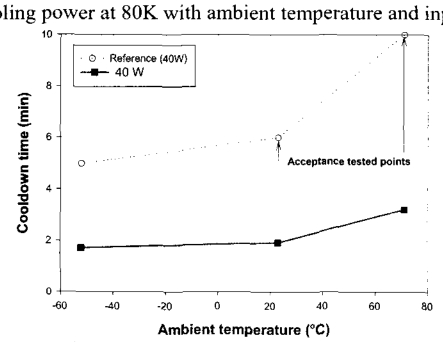
(a) Cooldown characteristics with ambient temperture



(b) Cooling power at +23°C with input power



(c) Cooling power at 80K with ambient temperature and input power



(d) Cooldown time to 80K with ambient temperature

Fig. 7. Performenace test results of the Stirling cryocooler.

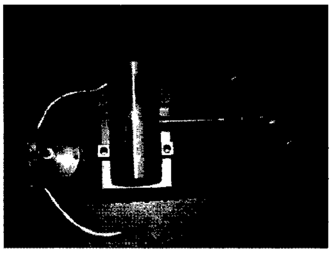
cooldown time to 80K with ambient temperature (d). As shown in Fig. 7 (a), cooldown time to 80K was the shortest and no load temperature was the lowest at +23 °C ambient. Cooling capacity at the input power of 40W and ambient temperature of +23 °C was 0.93W (Fig. 7 (b), (c)). This result was satisfied with the criterion of 0.8W in cooling capacity at the input power of 40W. Cooldown time to 80K at +23 °C ambient was 2 minutes, this result was satisfied with the criterion of 6minutes in cooldown time to 80K at +23 °C ambient (Fig. 7 (d)).

3.1.2. Vibration test

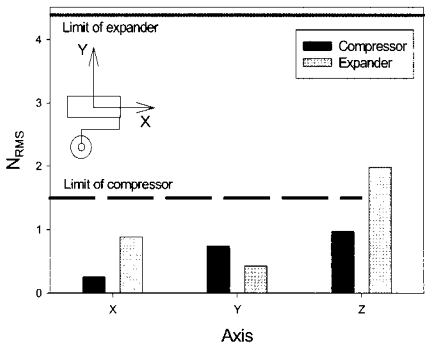
The vibration output force of the compressor and cold finger of the Stirling cryocooler shall not be greater than the values stated below in each of three mutually perpendicular axes at all frequencies up to 20 kHz.

- Compressor: 1.4 Nrms max.,
- Cold finger: 4.3 Nrms max.

Fig. 8 shows the vibration test apparatus and test results of the Stirling cryocooler. In Fig. 8 (b), red real line is the criterion of the vibration force for the expander and blue dotted line is the criterion of the vibration force for the compressor. The vibration output force of the compressor and cold finger of the Stirling cryocooler were smaller than the criterion of the vibration forces in each of three mutually perpendicular axes at all frequencies up to 20 kHz.



(a) Vibration test apparatus



(b) Vibration test results

Fig. 8. Vibration test apparatus and test results.

3.1.3. Acoustic noise test

Acoustic noise generated by the Stirling cryocooler does not exceed the criterion level displayed in Fig. 9, measured in a reflection free room at a distance of 5 meters. Fig. 9 shows test results for the acoustic noise of four Stirling cryocoolers. These test results are lower than the criterion of the sound level.

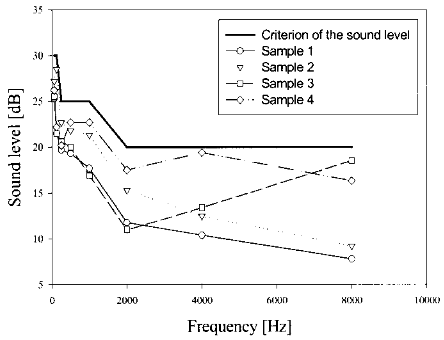


Fig. 9. Test results for the acoustic noise of Stirling cryocoolers.

3.1.4. Leak rate test

The Stirling cryocooler shall be placed in a suitable fixture(vacuum chamber) connected to a helium mass spectrometer(helium leak detector). The fixture shall be evacuated to establish an inside-out test mode. Fig. 10 shows schematic diagram for the leak rate test, and Table 4 displays test results for the leak rate. These test results are lower than the criterion of 6.0×10^{-9} Pa·m^3/s in the leak rate.

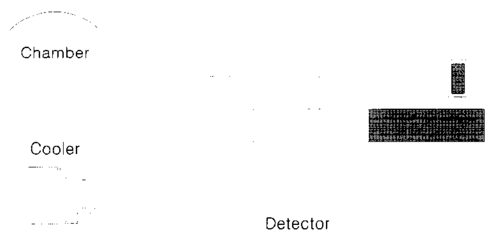


Fig. 10. Schematic diagram for the leak rate test.

TABLE 4.
Test results for the leak rate

Cooler	Leak rate
#1	1.1×10^{-9} Pa · m^3/s
#2	6.0×10^{-9} Pa · m^3/s
#3	1.1×10^{-9} Pa · m^3/s
#4	1.2×10^{-9} Pa · m^3/s
#5	1.2×10^{-9} Pa · m^3/s
#6	1.4×10^{-9} Pa · m^3/s
#7	6.0×10^{-9} Pa · m^3/s

3.2. Reliability test results

The MTTF test of the Stirling cryocooler was performed by room temperature test profile for the reliability cycle described in Fig. 6.

Fig. 11, Fig. 12, Fig. 13, Fig. 14 show the lowest temperature of the cold end temperature, input power, cooling capacity at the 80K and required time to 80K in the Stirling cryocooler, respectively.

In the case of initial operation, cooling capacity and required input power of Stirling cryocooler were 0.9W at 77K and 12W, respectively. However, after operation of 1200 hours, cooling capacity and required input power of Stirling cryocooler were about 0.72W at 77K and about 17W, respectively.

Cold end temperature was controlled with 80K during the MTTF test (Fig. 11), and according to operating time, input power increased slightly (Fig. 12). Cooling capacity of the Stirling cryocooler decreased (Fig. 13) and required time to 80K in cold end increased according to operating time (Fig. 14.).

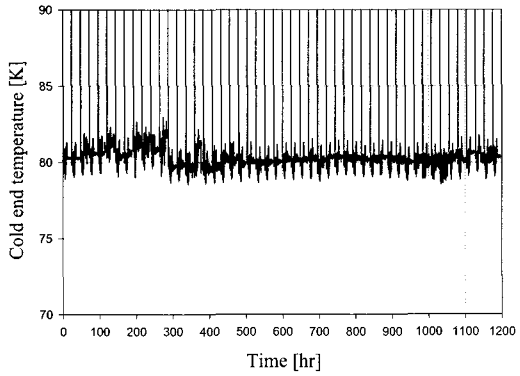


Fig. 11. Lowest temperature of the cold end during the MTTF test .

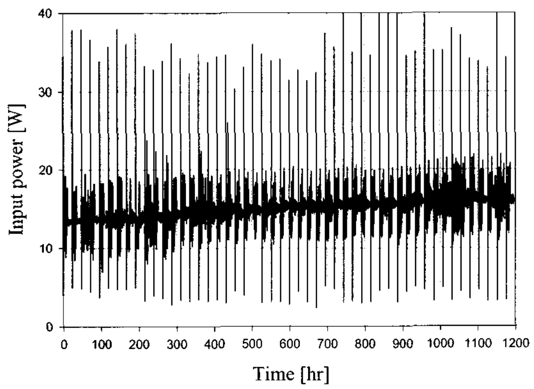


Fig. 12. Input power during the MTTF test.

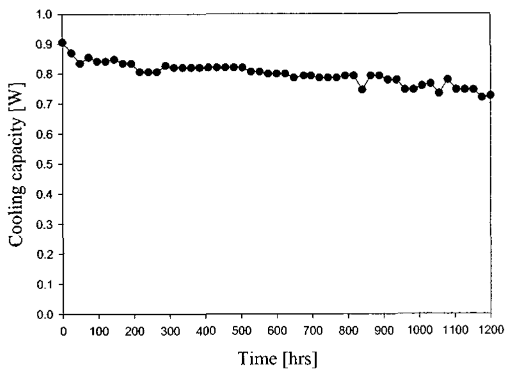


Fig. 13.Variation of the cooling capacity of the Stirling cryocooler.

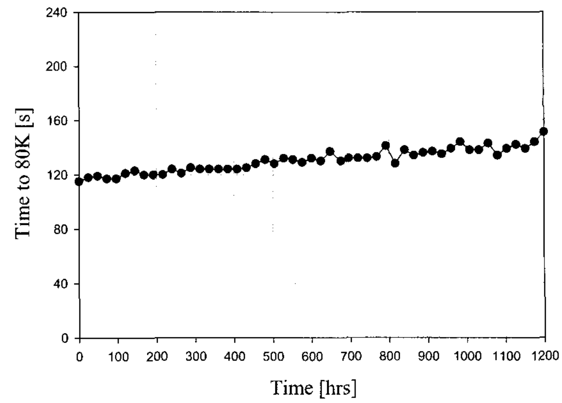


Fig. 14. Required time to 80K of the Stirling cryocooler.

4. CONCLUSION

Stirling cryocooler for cooling infrared detector was designed and fabricated. And a series of performance and reliability tests for the Stirling cryocooler were performed. The following conclusions are drawn from test results.

(1) Manufactured Stirling cryocooler delivered approximately 0.9W cooling at 80K for 30W ~ 40W of input power. And, it took approximately 2 minutes to cool down to 80K at the ambient temperature of 23℃.

(2) Performance characteristics for the vibration, acoustic noise and leak rate of the Stirling cryocooler were evaluated. Test results for the vibration, acoustic noise and leak rate of the Stirling cryocooler were lower than the limit levels, respectively.

(3) We performed that low and high temperature keeping test from -32℃ to +52℃ and operating test at high and low temperature cyclic range with acceptance tests performed at scheduled intervals.

(4) In initial operation, cooling capacity and required input power of Stirling cryocooler were 0.9W at 77K and 12W, respectively, but after operation of 1200 hours, cooling capacity and required input power of Stiling cryocooler were about 0.72W at 77K and about 17W, respectively

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