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High Efficiency Pressure Oscillator for Low-Temperature Pulse Tube Cryocooler

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HIGH EFFICIENCY PRESSURE OSCILLATOR FOR LOW-TEMPERATURE PULSE TUBE CRYOCOOLER

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ABSTRACT

Various applications require low cooling power at cryogenic temperatures in the range of 4 to 25K. Traditionally this type of cooling has been achieved by using Gifford-McMahon cryocoolers that use oil-lubricated compressors from the refrigeration industry, which have disadvantages in size and efficiency. An emerging alternative is a linear-pressure-oscillator driven pulse tube cryocooler developed by Sunpower, Inc. Pulse tube cryocoolers operate in a cycle similar to Stirling cryocoolers and offer potential advantages, including size and efficiency.

This paper will discuss the design, construction and testing of Sunpower's pressure wave generator for a three-stage pulse tube cryocooler funded by NASA Goddard Space Flight Center. The pressure wave generator is based upon Sunpower's proven oil-less linear compressor technology. The device is a 30Hz, dual-opposed free-piston design with 300 W_e of electrical input power and has demonstrated excellent dynamic balancing for low vibration, deep capacity modulation and PV-to-electrical conversion efficiencies as high as 90%.

1. INTRODUCTION

In the temperature range from 4 to 25K, low amounts of cooling power (from milliwatts to single watts) are necessary for markets such as vacuum cryopumping in the semiconductor industry, superconducting magnets for medical systems, and more recently superconducting electronic components for high-speed, low-noise communications (Weisand, 1998). The cryocoolers (refrigerators operating in the cryogenic temperature range) serving this market have predominantly been Gifford-McMahon cryocoolers that use large, steady-flow, oil-lubricated compressors from the refrigeration industry. To achieve the pressure oscillation required by the Gifford-McMahon thermodynamic cycle, a low-frequency (1-2 Hz) switching valve connects the high and low-pressure sides of the compressor to the cold head of the cryocooler. The disadvantages of this system include low PV-electrical efficiency due to the decoupling of the reciprocating compressor and the switching valve, the need for oil-removing equipment, excessive noise and large physical size and mass. The input power for these systems is typically in the range of a few kilowatts. Some emerging applications that need cooling in this regime, such as superconducting electronics for communications, require small and potentially mobile packages that cannot tolerate large size, inefficiency and vibration.

A promising alternative to the GM technology is a high-frequency pulse tube cryocooler developed by Sunpower, Inc. Advantages of this technology compared to GM cryocoolers include higher cooling efficiency, lack of moving parts in the cold head which reduces vibration, low noise level and more compact machines. Under funding from NASA Goddard Space Flight Center, Sunpower has built and tested a three-stage pulse tube cryocooler driven by a linear pressure wave generator.

A pulse tube cryocooler is similar in nature to a Stirling cycle cryocooler in which a working gas is compressed in a warm space and expanded in a cold space to produce refrigeration. In order for the cycle to operate correctly there needs to be a certain phase relationship between the mass flow rate of the working fluid and the pressure oscillation. In a Stirling cryocooler this phase relationship is accomplished by a mechanical component called the displacer. In a pulse tube cryocooler (PTC), this same function is accomplished by an adiabatic slug of gas, operating as a gas piston that is contained in a simple tube called a pulse tube. A schematic of a pulse tube cryocooler is shown in Figure 1. The thermodynamics of the cycle will not be covered here (the interested readers are referred to Radebaugh and Storch (1988)).

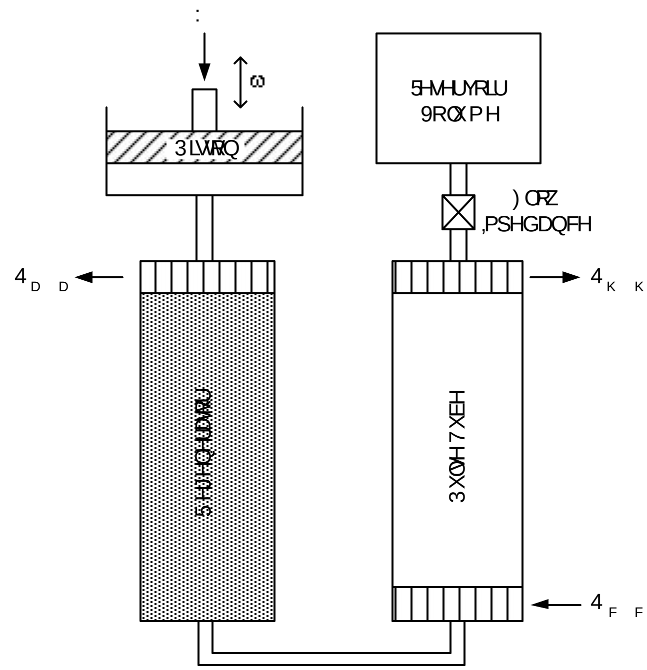

Figure 1. Schematic of pulse tube cryocooler.

Sunpower has been developing Stirling cycle cryocoolers for nearly 15 years and currently manufactures a line of low-cost commercial Stirling cryocoolers. In addition, Sunpower and Gedeon Associates have jointly developed pulse tube cryocoolers over the last 5 years and have demonstrated the technology at the laboratory prototype level. Both the Stirling and pulse tube cryocoolers use Sunpower's high-efficiency, patented linear compressor technology to generate the pressure oscillation. The focus of this paper is the pressure wave generator developed for the three-stage PTC for cooling at temperatures below 10K (Wilson and Gedeon, 2004).

2. SUNPOWER LINEAR COMPRESSOR DESIGN HERITAGE

The linear technology of the pressure wave generator is based upon over 12 years' linear compressor development for applications ranging from household refrigeration (Van der Walt and Unger, 1992) and air compression to specialty gas compression (Unger 1998) and CPU cooling (Unger and Novotny 2002). At Sunpower, linear compressors and pressure wave generators have been built from 10 W_e to 2.5 kW_e of input power, with compression ratios of less than 2:1 up to 26:1 in a single compression stage.

Sunpower's linear compressor is an axi-symmetric device with the piston driven by a linear motor (Redlich, 1986). The motor consists of permanent magnets attached to a structure called the magnet ring coupled directly to the piston (Unger, 1997). The piston/magnet assembly oscillates in an air gap created by two sets of steel laminations and a wound coil carrying alternating current. There is no conversion from rotary to reciprocating motion as in conventional compressors and thus the side loads normally transferred from the piston to the cylinder are virtually eliminated. Elimination of side loads enables the use of a gas bearing system (Unger, 2001) and oil-less operation. In the gas bearing system a portion of the high-pressure working fluid is directed around the piston to act as a lubricant on the running surfaces between the piston and the cylinder. This system prevents contact between the moving parts, offering long-life operation. Typically only 1-2% of the work-space pressure-volume (PV) power is consumed by the gas bearing system.

Most often planar springs are attached to the oscillating piston and used in conjunction with the gas spring of the work space to create a spring-mass system whose resonant frequency is at or near the operating frequency of the system. This reduces the amount of force that the motor needs to apply to the piston for a given amplitude and thus reduces the motor's size and losses. Since a portion of the total spring is composed of the gas spring in the work space, and the operating conditions in the work space can vary, the gas spring portion of the total spring can vary. In general, to provide a stable operating condition, the mechanical spring portion should be larger than the gas spring portion. However in certain situations the gas spring can be used without any mechanical spring. The mechanical springs are attached to the piston by a compliant member that reduces the side loads on the gas bearing system that may be caused by misalignment during assembly (Beale, van der Walt and Unger, 1996). The attachment of the piston to the spring through the compliant member also serves to center the piston axially. The combination of the linear motor, planar springs, gas bearings and a compliant member provides the following design advantages:

- Stability
- Readily manufactured (part tolerances and assembly)
- Modulatable for varying capacity
- Long life (non-contact clearance seals and running surfaces)
- High efficiency.

The general configuration of Sunpower linear compressor technology is shown in Figure 2.

3. PRESSURE WAVE GENERATOR REQUIREMENTS AND DESIGN

For the three-stage pulse tube cryocooler, the free-piston linear compressor technology did not require valves to create a DC flow as in a conventional linear compressor. The pulse tube cold head operates on a pressure oscillation directly coupled to the workspace created by the motion of the pistons. This is generally referred to as a pressure wave generator (PWG) rather than a compressor. Since a projected application of the cryocooler was for space missions, high efficiency and input power on the order of a few hundred watts was required as well as low levels of vibration and long life. Long life cryocoolers cannot tolerate oil due to its migration to the internal cold surfaces which then interferes with the thermodynamic process. Therefore the design was required to be oil-less. The very-low-temperature optimization of the cold head of the pulse tube cryocooler drove the PWG design to an operating frequency lower than that which Sunpower had previously built. Different potential operating conditions necessitated the capability to modulate the piston amplitude and thus cooling.

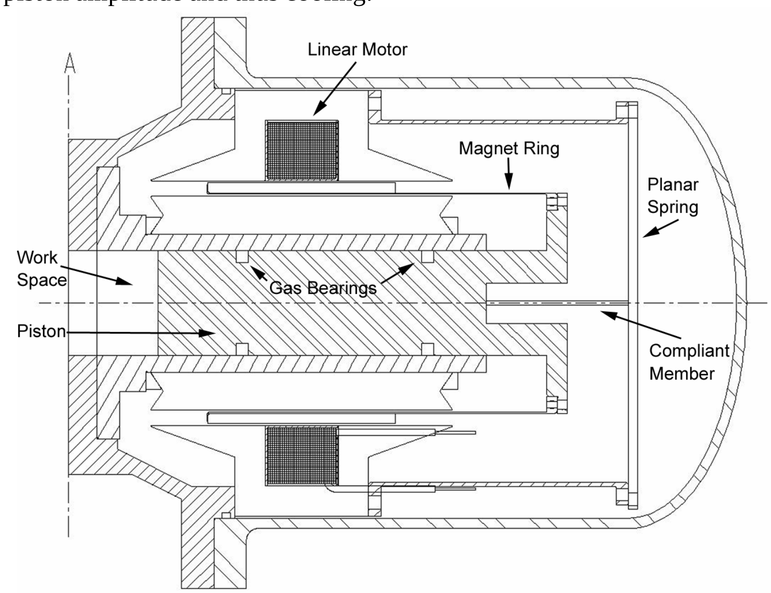

Figure 2. General layout of Sunpower linear compressor technology.

The design of the PWG was actually driven primarily by a need for swept volume amplitude of 12.6cc. The optimization of the pulse tube cryocooler cold head considers only swept volume, mean pressure and frequency as the input boundary conditions for the PWG. The major design trade between the performance of the cryocooler and the size of the compressor was encompassed in the operating frequency. Modeling suggested that lower frequency yielded more efficient cooling and lower no-load temperatures. However, the size and mass of the PWG varies as the inverse of the frequency. Thus lower frequencies began to yield a PWG that would be too large in physical size and mass considering that the cryocooler was being developed for a potential space program where real estate and weight are very important factors. So the frequency study was cut off at 30 Hz which became the design point.

Modeling suggested that we could achieve a low temperature of 5.5 Kelvin with 200 W PV power. Assuming a PV-to-electrical conversion efficiency of 85%, this resulted in 235 W_e theoretical input. This level of input power was acceptable for space application, but we still needed to address the vibration of the PWG. A dual-opposed configuration, created by reflecting the single-sided geometry shown in Figure 2 about axis A, was established for minimum vibration with each linear motor designed for 150 W_e input. This allowed for reserve capacity and faster cooldown rates with up to 300 W_e total input. Table 1 shows the features of the final design of the pressure wave generator. Components of the fabricated PWG as well as the completed assembly are shown in Figures 3 and 4, respectively.

Table 1. Features of dual-opposed pressure wave generator.

Physical Envelope	110 mm OD x 350 mm OAL (without flanges)
Mass	11 kg (with flanges)
Frequency	30 Hz
Electrical Power	150 W_e per side, 300 W_e total
Total Swept Volume	25.2 cc
Charge Pressure	25 bar
Nominal Pressure Amplitude	2 bar
Pressure Ratio (P_{max}/P_{min})	~1.2
Working Gas	Helium
Nominal Voltage	80 V_{AC}

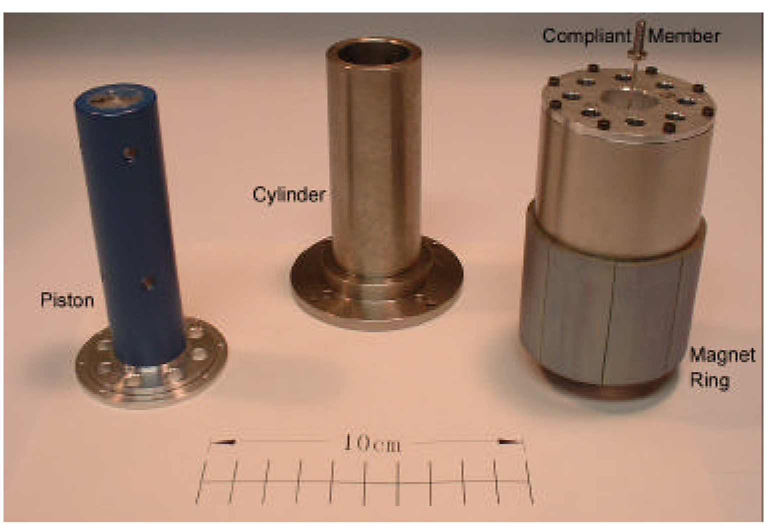

Figure 3. Components of linear motor and pressure wave generator.

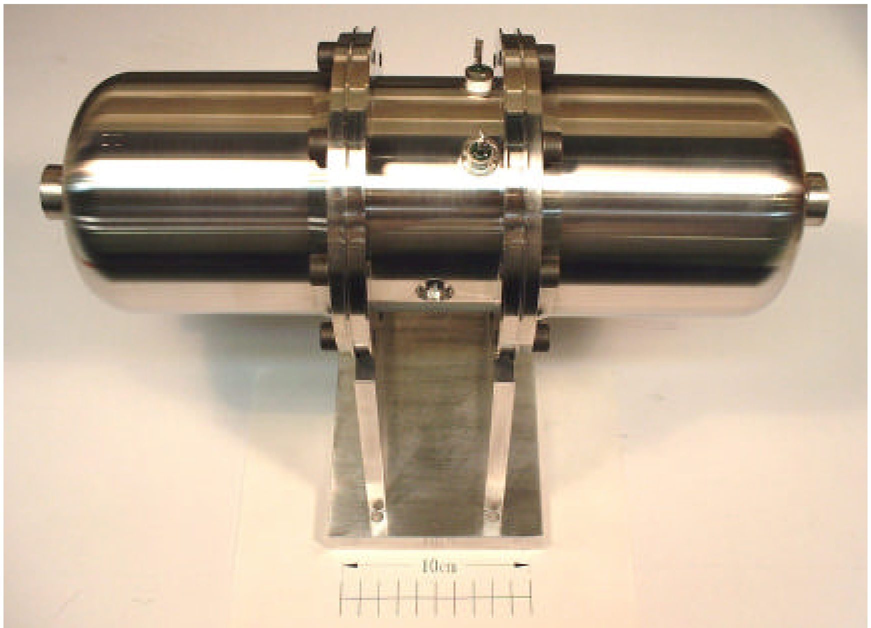

Figure 4. Dual-opposed linear pressure wave generator.

4. PRESSURE WAVE GENERATOR PERFORMANCE

The PWG was tested over a variety of conditions, from a single-stage cold head to a three-stage cold head, which mainly had an effect on the mechanical tuning of the system and also on the phase relationship between pressure and piston amplitudes. Vibration was never experimentally quantified, but the vibration level was very low simply assessed by touch. Figure 5 shows a map of compressor efficiency, in terms of converting electrical power to PV power, and predicted motor efficiency over a range of total input power

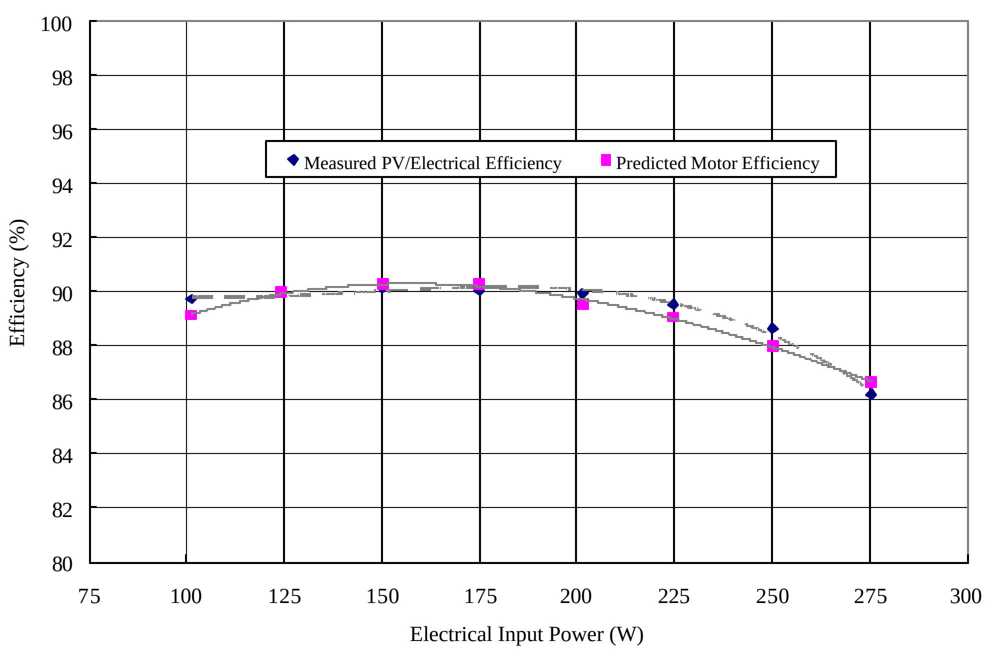

Figure 5. Map of PWG efficiency over a range of input power.

from 100 W_e to 275 W_e. The data for Figure 5 comes from a single run of the PTC and includes varying dynamic operating conditions, caused by the cold temperature decreasing from room temperature to 27K. Note that, within the instrumentation accuracy, the measured efficiency of the pressure wave generator is nearly equal to the predicted motor efficiency. This suggests losses due to factors such as friction, windage, and hysteresis are negligible.

The PV power data used in Figure 5 comes from cyclic integration of instantaneous pressure times volume flow rate (piston velocity) performed by the Labview data acquisition software. The results were routinely checked against a hand calculation for PV power in equation (1),

$$PV = A_P \cdot X_{AMP} \cdot P_{AMP} \cdot \sin(f_{P/X_P}) \cdot p \cdot f \qquad (1)$$

where A_P = piston frontal area (m^2)
X_{AMP} = combined piston amplitude of both pistons (m)
P_{AMP} = pressure amplitude (Pa)
$f_{P/XP}$ = phase angle between pressure and piston amplitudes (degrees)
f = operating frequency (Hz).

The comparisons were always found to be in very close agreement.

5. CONCLUSIONS

Sunpower's experience with linear compressor technology has been extended to the construction and testing of a pressure wave generator for a three-stage pulse tube cryocooler. The PWG had to meet various requirements for potential space applications, which led to the dual-opposed, oil-less, 30 Hz, 300 W_e PWG shown in Figure 4. Testing of the PWG demonstrated performance consistently above 87%, typically very near 90% efficient in the conversion of electrical power into PV power.

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