Performance Characterization of the TRW 3503 and 6020 Pulse Tube Coolers

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ABSTRACT

The Jet Propulsion Laboratory, under joint Ballistic Missile Defense Organization (BMDO)/ Air Force Phillips Laboratory and NASA/EOS Atmospheric Infrared Sounder (AIRS) sponsorship, has conducted extensive characterization testing of the TRW Model 3503 and Model 6020 pulse tube cryocoolers. These coolers, built under BMDO/AFPL sponsorship, share a common design that utilizes a single-stage pulse tube integrally mounted onto 10-cc common compression space compressors, and are distinguishable by slight differences in the pulse tube designs which optimized cooler performance for operation at either 35 K or 60 K. The coolers were characterized over a range of heat rejection temperatures and cooler operating parameters (compressor stroke, piston offset, and drive frequency) to understand their effects on cooler thermal performance, cooler-generated vibration and cold block motion, and cooler-generated EMI. Pulse tube parasitic conduction as a function of cold block temperature has been studied for a non-operating cooler; the results show a strong angular dependence relative to gravity. The results of the parametric studies are presented.

INTRODUCTION

The Air Force Phillips Laboratory has been developing pulse tube technology since 1992 when it awarded the 35 K Pulse Tube contract to TRW for development of a 1 W at 35 K pulse tube cooler using a 20-cc compressor. The overall objective was to improve pulse tube cryocoolers to be competitive with Stirling cryocoolers. TRW has significantly advanced the state-of-the-art of this technology in terms of performance, efficiency, and weight, thus enabling pulse tube cryocoolers to be competitive with Stirling coolers. Phillips Laboratory and the Jet Propulsion Laboratory (JPL) have teamed to fully characterize the coolers' performance.

JPL has recently completed extensive performance characterization of the TRW 3503 and TRW 6020 pulse tube coolers delivered under a Phillips Laboratory contract.[1] Characterization tests include varying environmental and cooler operating parameters to determine their effects on performance, off-state parasitics, self-induced vibration and EMI. The 3503 cooler provides a nominal 0.3 watts of cooling at 35 K with 80 watts of input power to the cooler; the 6020 provides a nominal 2.0 watts of cooling at 60 K with 80 watts input power to the cooler. The TRW 3503 and 6020 pulse tube cryocoolers are very similar in design. The compressor design consists of two 5-cc back to back flexure-bearing compressors compressing the helium working fluid in a common compression space. The pulse tube is integrally mounted to the center plate of the compressor. The pulse tube cold head designs are also very similar, with only slight differences between the cold heads to optimize the cooler performance for either 35-K or 60-K operation, respectively. The two 10-cc coolers are shown side-by-side together with their laboratory drive electronics in Fig. 1. The coolers are driven with low-distortion audio amplifiers and sinusoidal voltage waveforms. While there is no active temperature and vibration control for these cryocoolers in the present electronics, a separate effort is underway to develop this capability for space flight application. The TRW model 6020 cryocooler, with slightly modified interfaces, has been selected for the Multispectral Thermal Imager space mission in 1998. The characterization testing of these 10-cc coolers has provided very informative and timely performance results for the JPL Atmospheric Infrared Sounder (AIRS) instrument.[2] The AIRS flight cooler in development by TRW also uses a 10-cc compressor and has similar thermal performance requirements.[3] There are several significant design differences in the AIRS cooler which has lengthened the development effort of this cooler. With the build of the AIRS engineering model instrument in progress, the TRW 3503 and 6020 cooler characterization results have helped finalize the design of the AIRS cooler and the planned thermal vacuum tests of the integrated AIRS engineering model instrument.

REFRIGERATION PERFORMANCE

Thermal Performance

Separately, each cooler was mounted in a thermal-vacuum chamber on thin-walled stainless steel standoffs to minimize thermal conduction to the chamber. Copper heatsink plates with

Figure 1. The TRW 3503 (left) and TRW 6020 (right) pulse tube coolers.

temperature controlled fluid loops were attached to opposing sides of the compressor center plate to simulate the heat rejection in a spacecraft implementation. The two coolers were comprehensively tested over similar coldblock temperature ranges (35 K to 100 K) with similar variations in the operational and environmental operating parameters — compressor piston stroke, piston position offset, drive frequency, and heat sink temperature — to provide performance sensitivity measurements with respect to each of these parameters. Thermal performance measurements of the pulse tube coolers are plotted on multivariable plots devised by JPL to describe the cooler thermal performance dependence on the cooler input power, coldtip load, cold block temperature, specific power, and other operational parameters.

Piston offset. Piston offset is a shifting of the piston neutral position towards or away from the compression end of the cylinder. A positive offset moves the pistons towards the compression end of the cylinder, and has the effect of reducing head room and cooler dead volume. This offset effects the peak-to-peak pressure ratio for a given stroke, and becomes increasingly important at lower compressor strokes. This parameter was examined first. Each cooler was operated at the nominal 11-mm operating stroke, and cooler performance was measured as a function of cold block load for different dc offset positions for the pistons; the optimal offset was used throughout the remainder of the thermal performance tests. The 3503 cooler was found to operate more efficiently with a +1-mm offset over the 35-K to 100-K temperature span, whereas the 6020 cooler was operated at zero offset, since its thermal performance was rather insensitive to piston offset. Figures 2 and 3 show the sensitivity of the thermal performance to piston offset.

Compressor stroke. Figures 4 and 5 show the overall thermal performance of the respective 3503 and 6020 coolers as a function of compressor stroke. The nominal operating stroke for both coolers was 11-mm (about 70% of full stroke). As can be seen in comparing the graphs, the 3503 cooler, optimized for 35 K operation, is able to reach lower cold block temperatures although requiring higher cooler input power at a given stroke than the 6020 cooler. The 3503 cooler was able to provide 350 mW of cooling at 35 K for an input power of 105 watts, whereas for the same input power the 6020 cooler was unable to cool below 37 K. At 60 K, both coolers are able to produce 2 watts of cooling with approximately 80 watts of cooler input power. Above

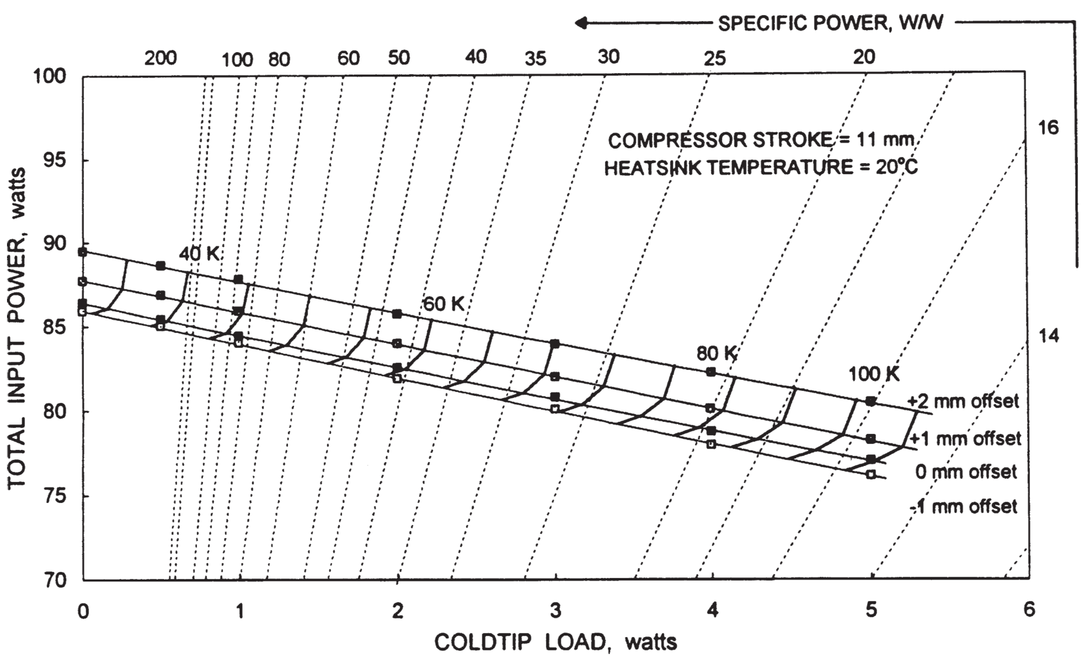

Figure 2. Sensitivity of the 3503 cooler thermal performance to piston offset.

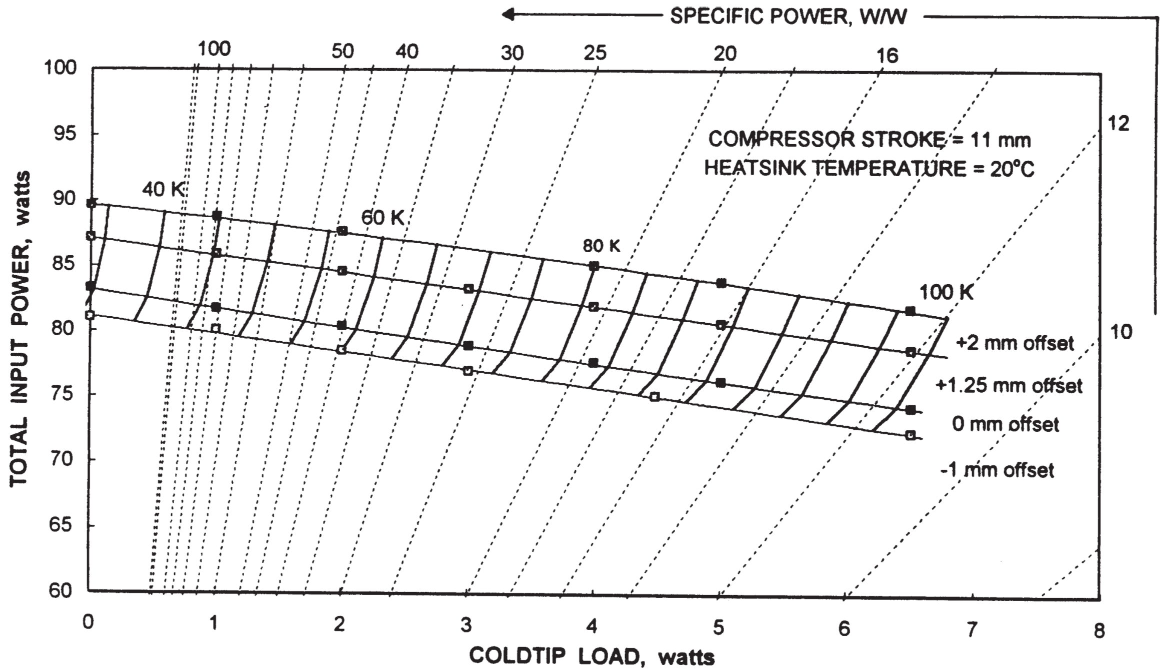

Figure 3. Sensitivity of the 6020 cooler thermal performance to piston offset.

60 K the 6020 performs more efficiently for a given cold block load and temperature. As can be seen from the figures, cooler efficiency is a strong function of the stroke at the lowest temperatures, with improved efficiencies for higher strokes. Around 60 K, cooler efficiencies are insensitive to wide stroke variations.

Drive frequency. Cooler performance for each cooler was measured at the 11-mm operating stroke for several different drive frequencies ranging between 40 Hz and 48 Hz to demonstrate the performance sensitivity to cooler drive frequency (See Figs. 6 and 7). Nominal operating

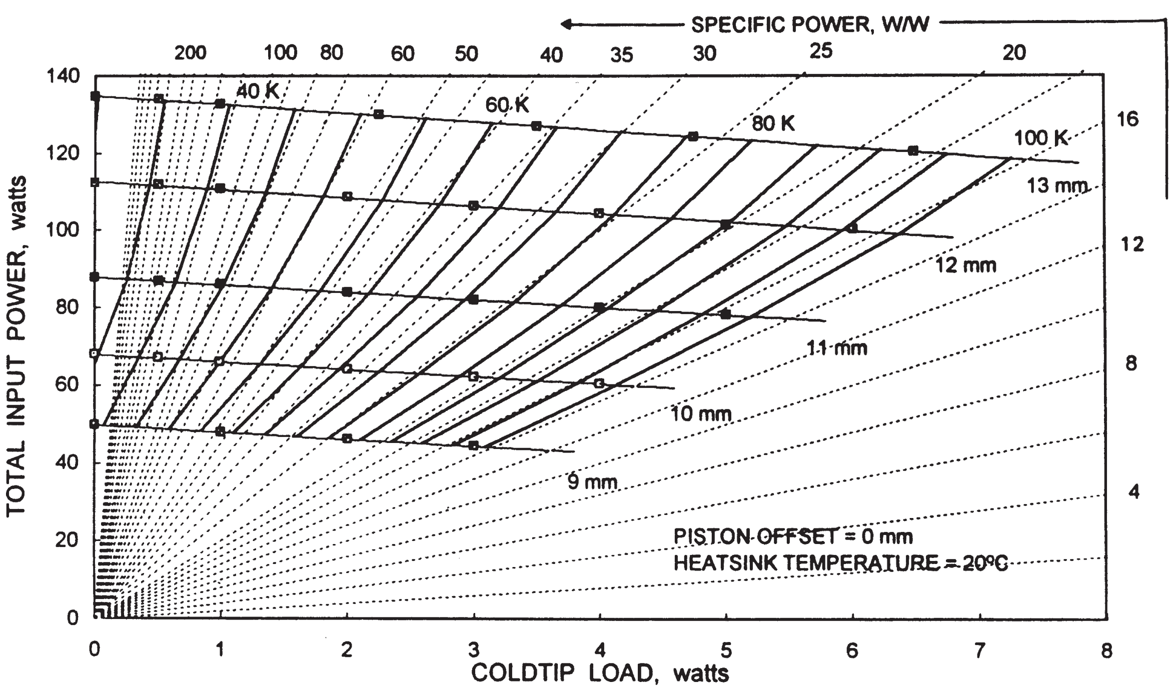

Figure 4. Sensitivity of the 3503 cooler thermal performance to compressor stroke.

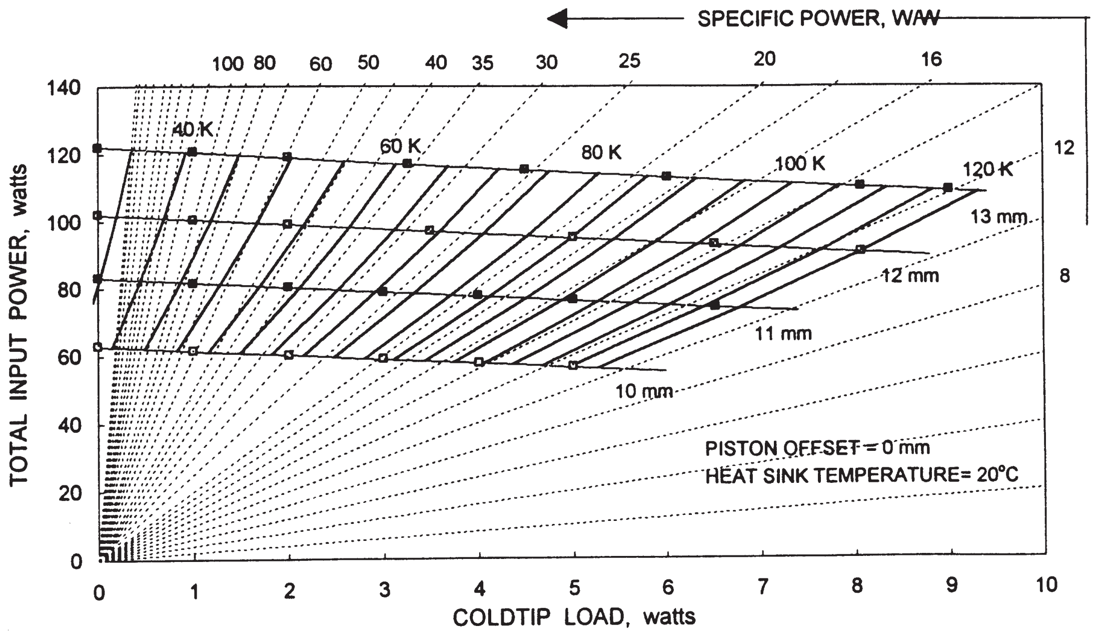

Figure 5. Sensitivity of the 6020 cooler thermal performance to compressor stroke.

drive frequencies are 46 Hz for the 3503 cooler, and 44 Hz for the 6020 cooler. Note that at the suggested drive frequency for each cooler the cooling capacity and the specific power are optimum for temperatures below 60 K; above 60 K, the efficiency of each cooler improves with slightly lower drive frequencies.

Heat sink variation. Figure 8 depicts the change in thermal performance of the 3503 cooler due to a change in heat sink temperature from 0°C to 40°C for a constant 11-mm stroke. There is a very significant improvement in efficiency, both with improved cooling capacity and with decreased input power by operating at the lower heat sink temperature. At higher temperature, efficiency continues to improve with lower sink temperatures. Figure 9 demonstrates the shift in

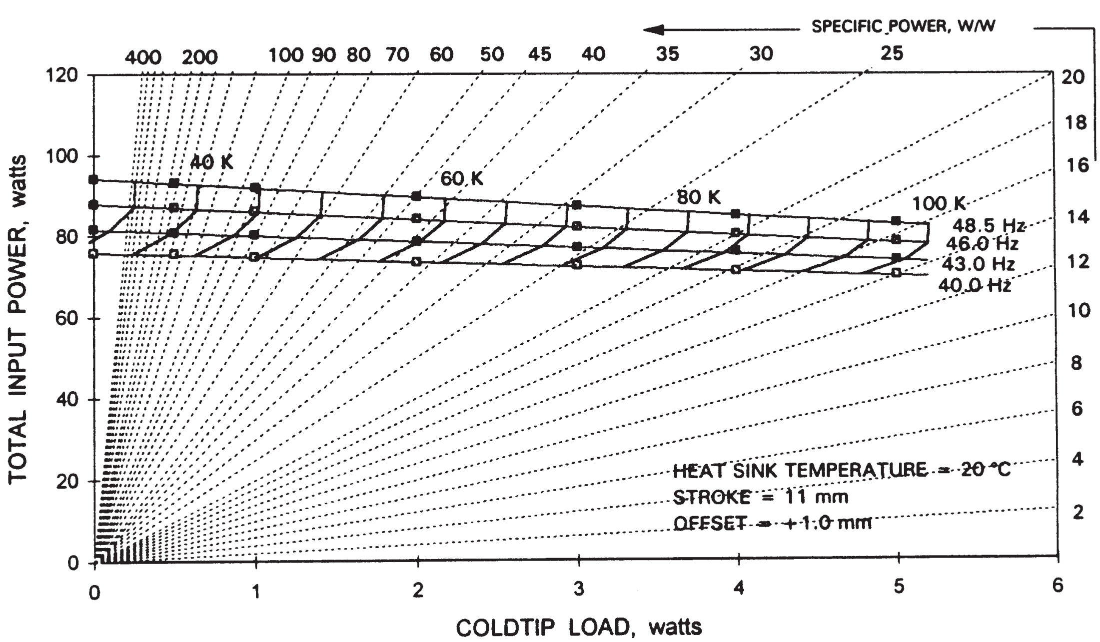

Figure 6. Sensitivity of the 3503 cooler thermal performance to drive frequency.

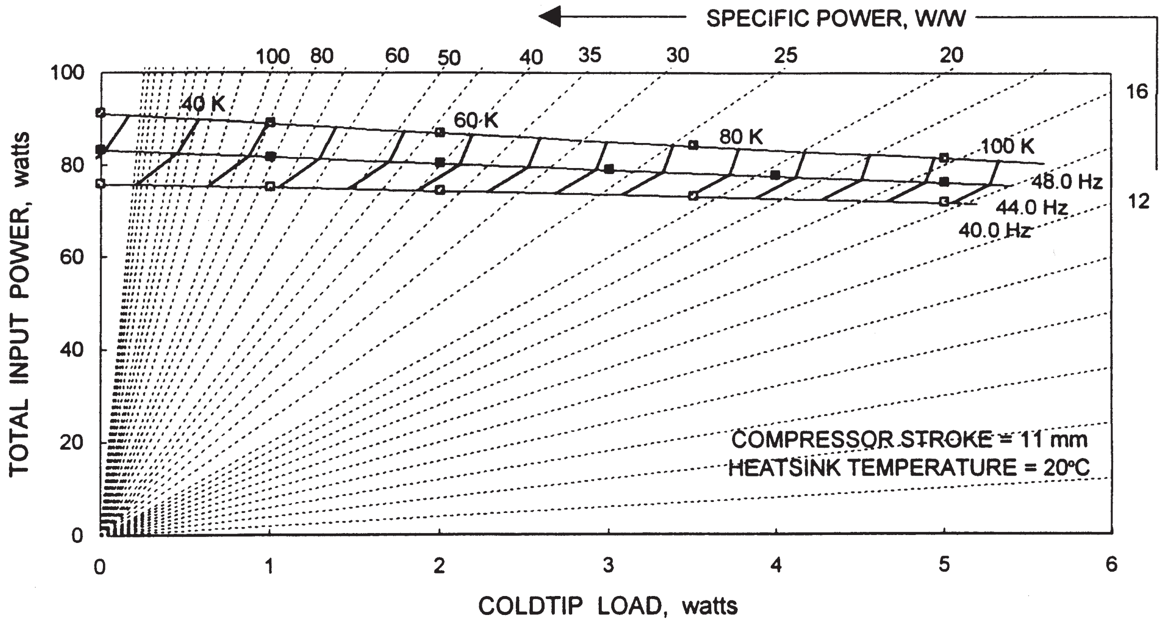

Figure 7. Sensitivity of the 6020 cooler thermal performance to drive frequency.

isotherms between the 11-mm and 13-mm stroke conditions for the heat sink variation between 20°C and 0°C. The 20°C change in sink temperature can result in as much as a 40-watt change in input power for the same cooling load and coldblock temperature. Similar performance improvements with reduced heat sink temperatures were observed with the 6020 cooler but are not presented here. Heat sink temperatures were monitored at the copper heat sink plates bolted to the compressor center plate. Prior to operating the cooler at either 0°C or 40°C heat sink temperature, each cooler was driven at full stroke at very low frequencies (0.002 Hz to 0.005 Hz) to make stiction measurements to insure there was no rubbing of the piston due to differential thermal contraction mismatches.

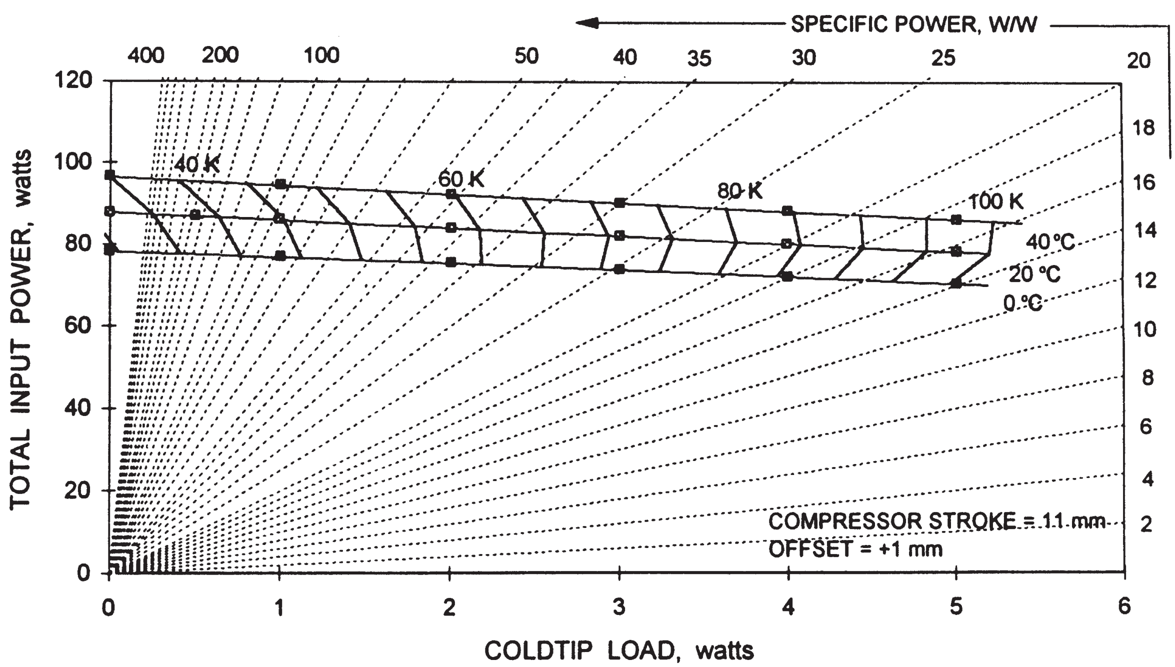

Figure 8. Sensitivity of the 3503 cooler thermal performance to heat sink temperature.

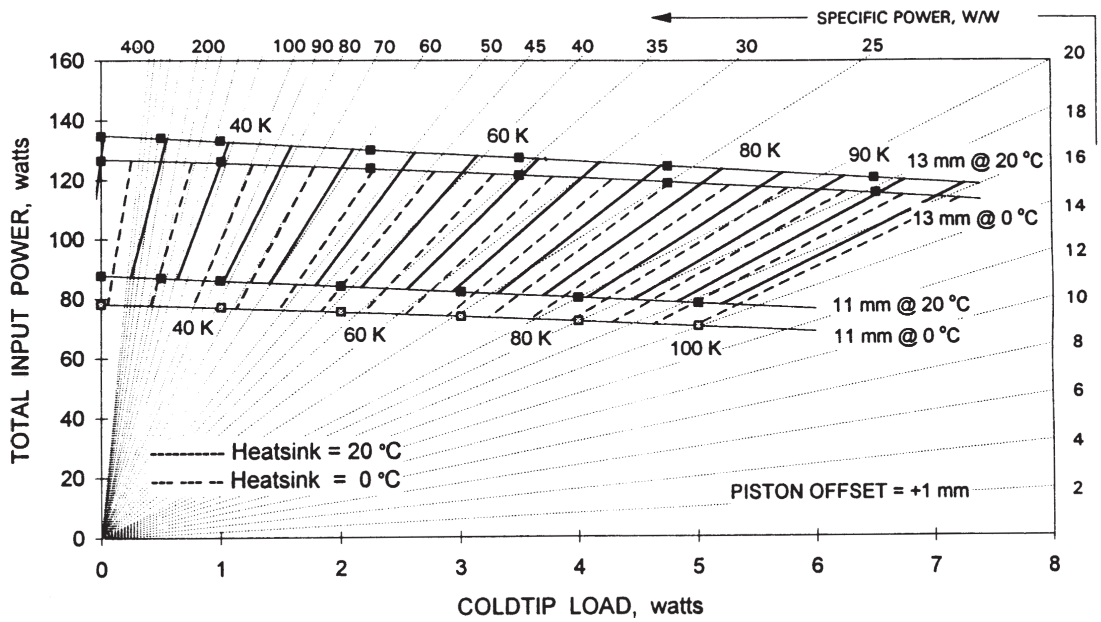

Figure 9. Sensitivity of the 3503 cooler specific power to heat sink temperatures.

Cooler Efficiency

The figure of merit for cryocoolers, the thermodynamic coefficient of performance (COP), is defined as the ratio of the net cooling power to the net applied input power (input electrical power$-i^2R$ heating of the coil), and is expressed as a percentage of the ideal Carnot COP. The 3503 cooler, operating with an 11-mm stroke and 20°C heat sink, ran at about 2% of Carnot efficiency at 35 K, increasing to 4% at 35 K by reducing the heat sink temperature to 0°C. It also operated more efficiently with higher compressor strokes. The 6020 cooler operated with a Carnot efficiency near 12% at 60 K. Similar levels of Carnot efficiency were observed at 60 K for the 3503 cooler. Motor efficiencies ranging between 80% to 88% were measured for the coolers under the various operating conditions. Motor efficiencies are dependent on the i^2R losses within the coil. In general, motor efficiencies were found to increase with decreasing stroke, increasing cold block temperature for a given stroke, decreasing drive frequency, and increasing heat sink temperature. Motor efficiencies were highest at the optimal dc piston offset condition. The measured power factors for the motors of the coolers range from 0.8 to as high as 0.96. The power factor is defined as the ratio of the true rms input power to the product of the measured true rms voltage and true rms current. The observed power factor followed the trends of the motor efficiency, that is, the power factor improved with decreasing stroke, decreasing drive frequency, and increasing heat sink temperature.

OFF-STATE CONDUCTION

An important consideration in the use of redundant coolers is the parasitic heat load placed on operating coolers by the non-operating or standby coolers. Because the parasitic load can be a substantial fraction of the available cooling power at cryogenic temperatures, accurate data on these off-state loads are essential. Heat transfer parasitics through the pulse tube of the non-operating pulse tube cryocooler were measured for both the 3503 and 6020 cryocoolers using an equilibrium heat conduction measurement technique.[4] In the test configuration, the pulse tube is enclosed in a vacuum housing together with the coldfinger of a second cryocooler that is used to cool the cold block of the pulse tube cooler down to typical flight-operating temperatures. An absolute heat-flow transducer measures the resulting heat flow passing through the pulse tube.

The measured parasitic conduction levels were very similar for the two pulse tube coolers. Figure 10 shows the measured parasitic heat flow through the pulse tube of the 6020 cooler as a function of coldblock temperature for three pulse tube orientations with respect to gravity. The most favorable position for the pulse tube is to be positioned vertically, with the ambient temperature orifice block positioned above the coldblock. In this orientation the helium gas becomes highly and stably stratified, limiting the free convection of the helium gas that causes the high conduction rate. Note that for coldblock temperatures below 90 K, the heat transfer parasitics are largest when the pulse tube is lying horizontal with respect to gravity. In all pulse tube orientations, the parasitic conduction levels increase rapidly as the coldblock temperature is reduced below 50 K. This phenomenon has not been studied in detail, but appears to be a result of the pulse tube gas dynamics, as opposed to an experimental effect. The orientation dependence of the heat transfer parasitics through the pulse tube was examined in detail at 60 K. Figure 11 demonstrates the dramatic change in the parasitic conduction at 60-K as the pulse tube is rotated from vertical (0 degrees) to the inverted orientation. Little change in the parasitic conduction level is seen until the pulse tube has been rotated from vertical to 80 degrees with respect to vertical. There is a dramatic rise in conduction as the pulse tube is further rotated through the horizontal position and is pointed downward, reaching a maximum value of nearly 3.5 watts at an angle of 130 degrees with respect to vertical, before decreasing again as the pulse tube is rotated through to the inverted position. In the inverted orientation the pulse tube is observed to have a conductance level twice that of the vertical orientation.

GENERATED VIBRATION

The measurements of the vibration generated by the pulse tube coolers were conducted in the JPL cryocooler vibration characterization facility using a special-purpose six degree of freedom dynamometer.[5] The TRW coolers were mounted with the compressor aligned in the vertical direction. This facilitated the gathering of data for the moment about the piston axis along with the force vectors in the x, y, and z directions.

Compressor Vibration

Vibration measurements were made as a function of such parameters as the drive frequency, the compressor stroke, the piston offset, and the coldblock temperature. The back-to-back compressor configuration facilitated the minimization of the vibration along the piston axis at the

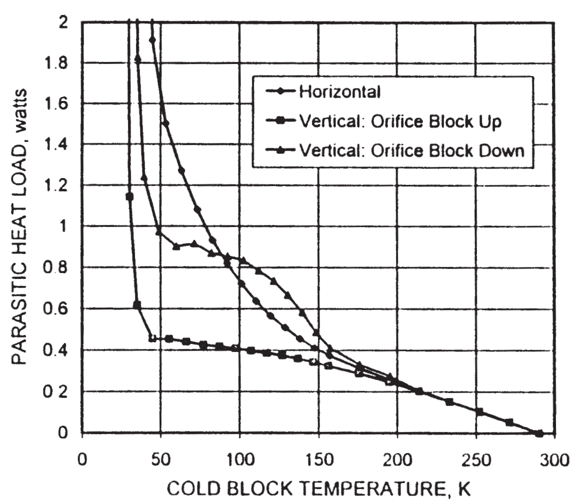

Figure 10. Heat flow parasitics of the 6020 cooler as a function of cold block temperature.

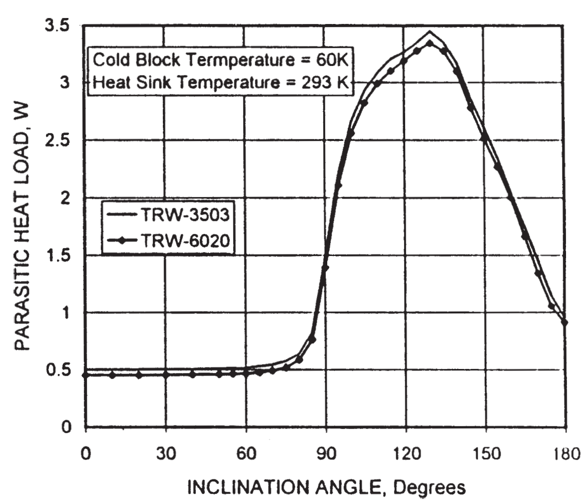

Figure 11. Heat flow parasitics as a function of inclination angle (0° refers to vertical orientation).

fundamental harmonic by trimming the stroke of one of the two compressors. There was no provision available with the laboratory drive electronics for multi-harmonic vibration cancellation. A sample of the vibration levels measured for various piston strokes are shown for the two coolers in Figs. 12 and 13. The z-axis is the vertical axis measured along the piston axis, the x-axis is pointed along the pulse tube. Although identical in build, the vibration signatures from the two 10-cc compressors are significantly different. The measured vibration levels for the 3503 cooler were typically between 0.1 N and 1.0 N, the larger value being for a harmonic in the piston axis. Vibration levels typically fell off with increasing harmonics. The vibration levels for the first few harmonics for the 6020 cooler were similar to the 3503 cooler in all axes. However, the vibration levels of the higher harmonics of the 6020 did not fall off, but, rather, were at or above the vibrational levels of the first few harmonics. The 6020 vibration levels could be reduced by running the cooler at 46 Hz.

Coldblock Motion

The motion of the coldblock was also measured as a function of several operating parameters, such as drive frequency, piston stroke, etc. This motion was measured while the compressors were mounted on the dynamometer, using a set of three miniature cryogenically coolable accelerometers mounted on the coldblock and aligned to the same axes as the force sensors. Measured coldblock motions in the pulse tube direction were on the order of 1 to 2 μm, and an order of magnitude lower in the pulse tube transverse directions. These motions were rather insensitive to changes in operating parameters. However it was possible to excite the transverse bending mode of the 6020 pulse tube around 264 Hz.

EMI/EMC

Measurements of the radiated electric and radiated magnetic field emissions were made on the 3503 cooler operating at a nominal 80-W input power to the compressor (11-mm stroke). The cooler was placed in an RF-shielded room and grounded to a copper laminated table; the cooler

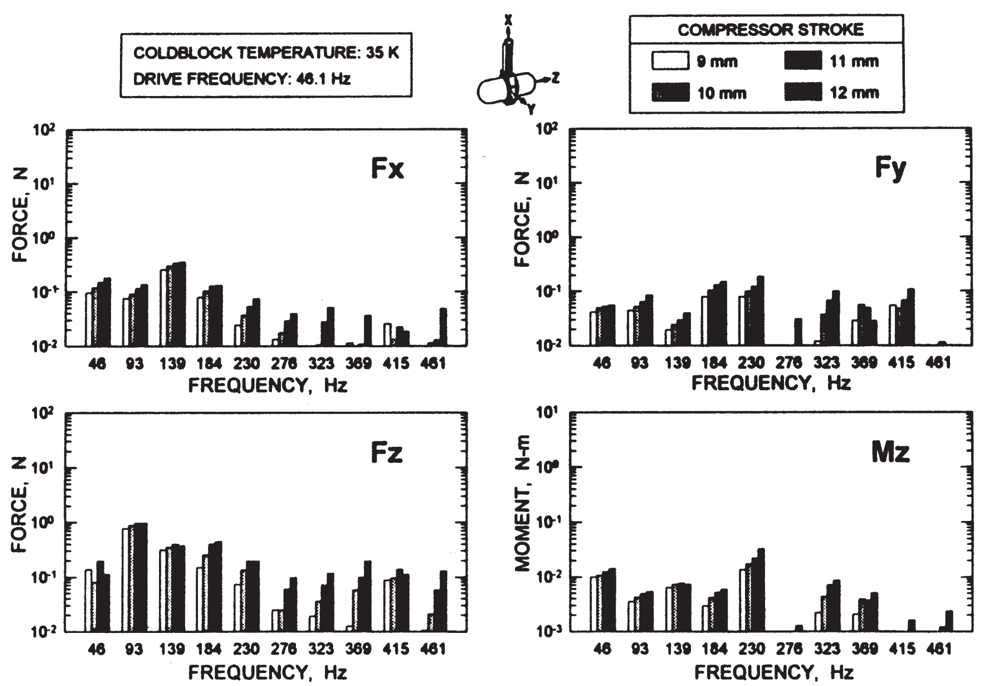

Figure 12. Sensitivity of the 3503 cooler-generated vibration to compressor stroke.

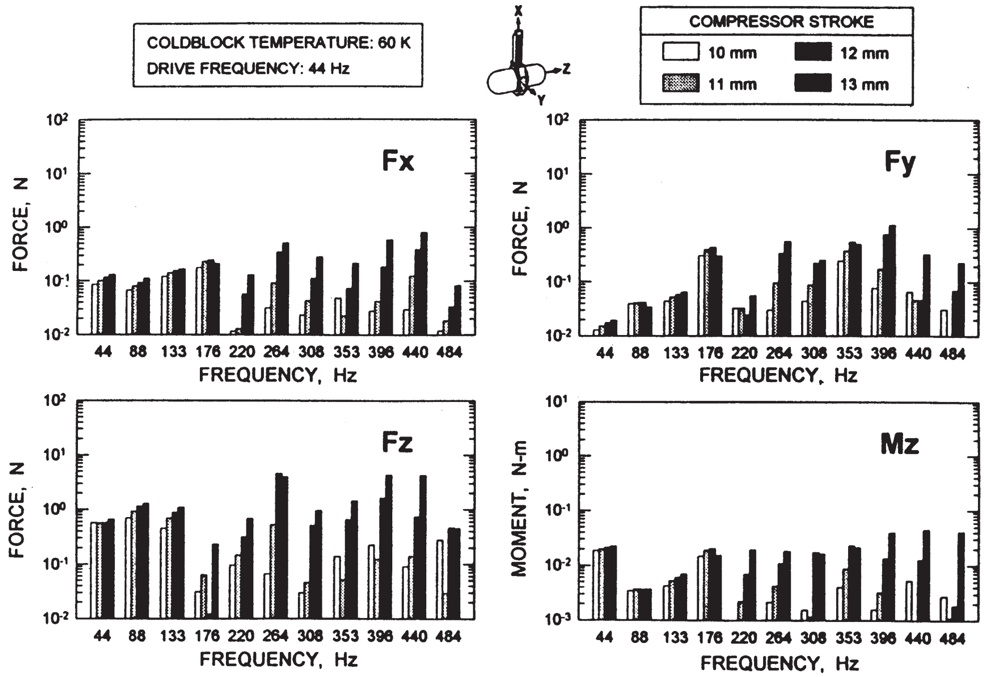

Figure 13. Sensitivity of the 6020 cooler-generated vibration to compressor stroke.

electronics were placed in an adjacent room with the cabling fed through a bulkhead in the wall. The cabling was sheathed in aluminum foil and grounded to the copper table top to minimize any contributing radiation. Measured levels for the radiated AC electric field emissions were well below the specification limits of Mil-STD 461C RE02. The AC magnetic field emissions were measured at distances of 7 cm and 1 meter from the cooler. Figure 14 depicts the radiated magnetic emissions measured at 7 cm from the 3503 cooler. Typical of linear voice coil compressor designs, the radiated magnetic emissions of the first few harmonics exceeded the specifications under MIL-STD 461C RE01 and MIL-STD 461C RE04.

SUMMARY

The effort described herein was a unique opportunity to test two pulse tube coolers from the same build. The TRW 3503 and 6020 pulse tube coolers were constructed using the same 10-cc compressor design, but optimized for their intended 35-K or 60-K operating temperature. The 3503 cooler provided a nominal 0.3 watts of cooling at 35 K with 80 watts of input power to the cooler. The model 6020 provides a nominal 2.0 watts of cooling at 60 K with 77 watts input power to the cooler. Both coolers were characterized in terms of their thermal performance, off-state parasitic conduction, and the generated vibration. Thermal performance sensitivity studies were conducted with respect to key operational and environmental parameters, including compressor stroke, piston offset, drive frequency, and heat sink temperature. The pulse tube off'-state parasitic conduction was found to be very sensitive to the pulse tube orientation with respect to gravity. Measurements of the parasitic conduction were made both as a function of coldblock temperature for several fixed pulse tube inclination angles, and also at a fixed temperature for inclination angles between 0° and 180° with respect to gravity. Cooler-generated vibration measurements provided quite different vibration signatures between the two pulse tube coolers. EMI measurements made with the 3503 cooler showed magnetic emissions exceeding the MIL-STD 461C specification, typical of compressors utilizing flexure-bearing supported linear motor designs.

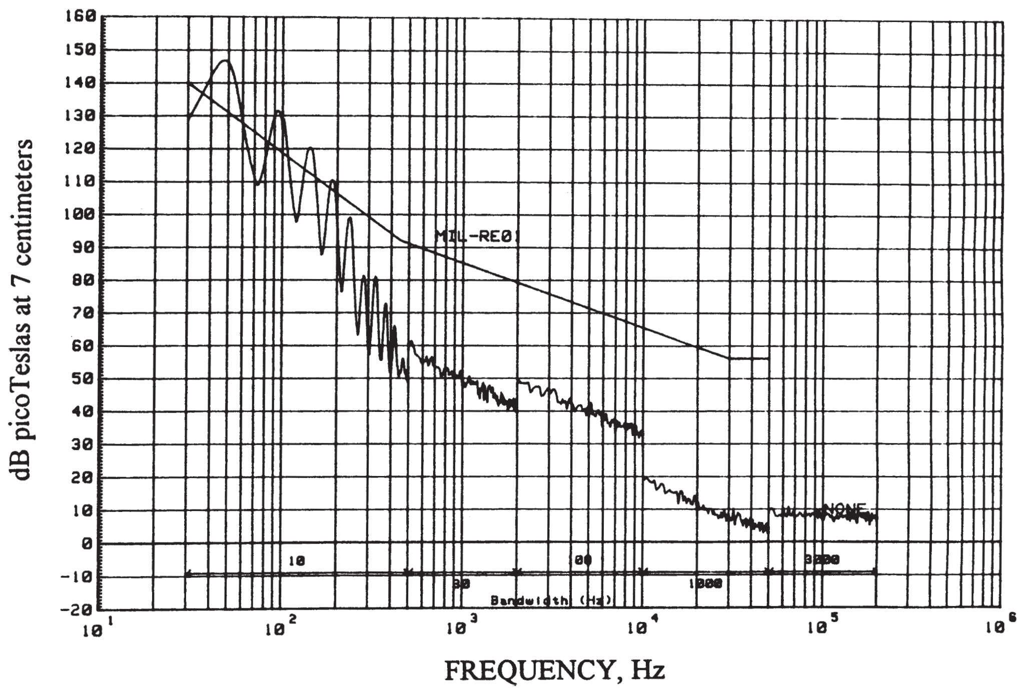

Figure 14. Radiated magnetic emissions measured at 7 cm from the TRW 3503 cooler operating with a nominal 80 W input power to the cooler.

ACKNOWLEDGMENTS

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