Thermal and exported vibration characterization of RICOR K508N cryocooler

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Abstract. The RICOR K508N is an upgraded version of the K508 that has extensive flight heritage. This paper reports on the thermal performance and exported force results for a COTS K508N for the ATACOI project as well as two K508N coolers filled to a higher fill pressure and with a high frequency motor for the CIRAS mission. The thermal performance of the coolers was measured in vacuum for -40°C, 20°C and 57°C heat reject temperatures. The coolers were operated in open-loop and in closed-loop mode during thermal performance testing. The K508N for ATACOI was put through Protoflight/Qualification thermal vacuum testing in order to satisfy JPL environment requirements for flight. Exported vibration results for the ATACOI, CIRAS and MASPEX coolers are presented and compared. Finally, the ATACOI K508N was tested with and without wire rope vibration isolators to validate the results presented in Ref. [11]. As a result of increased fill pressure and a high frequency motor, the CIRAS coolers showed a 22% performance improvement at 90 K compared to the ATACOI cooler.

1. Introduction
The RICOR K508 Stirling-cycle rotary integral refrigerator has been used for many space and ground-based applications since its inception in the 1990’s [1]. The K508N was introduced as an improvement on the K508 with the intention of doubling its reliable operation hours to 20,000 under standard working conditions [2]. Four of these coolers were put through various tests at the Jet Propulsion Laboratory (JPL) to better understand their thermal performance and exported force characteristics for flight applications. The first was a commercial off-the-shelf (COTS) K508N that was purchased for the Advanced Thermal Architecture for Cryogenic Optical Instruments (ATACOI) project, which is managed and funded by the Small Spacecraft Technology Program within NASA’s Space Technology Mission Directorate. ATACOI aims to advance the technology readiness level of a pumped fluid loop based thermal subsystem for optical instruments on a 6U CubeSat that takes advantage of additive manufacturing to save volume and mass [3, 4]. Specifically the project will demonstrate that the heat generated by an operating K508N can be intercepted by the pumped fluid loop and rejected to space via by a deployable radiator. The second two coolers were flight quality provided through RICOR’s selection and customization process, described in Ref. [1], that were purchased for the CubeSat Infrared Atmospheric Sounder (CIRAS) project [5]. The final was the engineering model of the K508N that will be used on the Mass Spectrometer for Planetary Exploration (MASPEX) instrument for the Europa Clipper project [6] with custom flight electronics built by Iris Technologies. This paper describes the testing these various K508N coolers underwent at JPL.
2. Thermal Vacuum Tests

2.1. Test setup description

Three of the K508N coolers described above were tested in a vacuum chamber and were configured similar to what is shown in Figure 1. The coolers were attached to a cold plate that was fed by an FTS RTC211 chiller and temperature controlled with a resistive heater circuit, a silicon diode, and a Lakeshore 336 controller. A copper block supporting three silicon diodes and a 1,500 Ohm resistor was clamped to the cold tips with an indium interface. The cold tip of each cooler was oriented downward to minimize natural convection. The heat rejection temperature of the coolers was defined as the temperature of the cold plate and was varied from -40°C to 57°C while the cold tip heat load was varied from 0 W to 3 W. To fully characterize the coolers, both closed-loop and open-loop data was collected. For open-loop operation, the leads of the RICOR control thermometer input were shorted so that the cooler constantly ran at its maximum power. For closed loop control, a 10 kilohm potentiometer was added in series with a silicon diode and fed back to the RICOR control thermometer input. The potentiometer dissipated some of the voltage output from the diode allowing different setpoint temperatures to be achieved. The potentiometer was adjusted until the cooler controlled at a desired temperature. Data was collected at isotherms between 70 K and 240 K. For both control methods, a LabVIEW program communicated with a power supply and stepped through a list of cold tip heat loads. The program would move on to the next heat load once steady state was achieved.

2.2. ATACOI RICOR K508N testing

All open and closed-loop data on the ATACOI K508N was taken at the nominal input voltage of 24 VDC and with a helium fill pressure of 35 bar. Error! Reference source not found. shows a Ross plot of thermal performance data taken for the ATACOI cooler (SN 57-08234). Isotherms of 120 K, 180 K and 240 K are not shown for clarity. The cooler was able to lift a maximum of 0.66 W at 90 K with a -40°C reject temperature. All of the closed-loop data collected on this cooler was curve fit into a polynomial that can predict the necessary input power ($P_{in}$) based on reject temperature ($T_{rej}$), cold tip temperature ($T_{CT}$), and cold tip heat load ($Q_{CT}$). The equation is valid for input power between 3 W and 16 W, reject temperatures between -40°C and 57°C, cold tip temperatures between 70 K and 240 K, and cold tip heat loads between 0 W and 2.4 W. The equation was generated by fitting $P_{in}$ vs $T_{CT}$ for fixed $Q_{CT}$. Next, the coefficients of these polynomials were fit against $P_{in}$. Then the resulting coefficients were fit as a function of $T_{rej}$. In all, 65 coefficients were necessary to keep the relative error in prediction below 5%. Equation 1 combines all the coefficients and Table 1 defines all of their values.
Figure 2: Ross Plot of ATACOI Cooler Performance. RICOR K508N S/N 57-08234.

\[ P_m(Q_{CT}, T_{CT}, T_{ref}) = A T_{CT}^6 + B T_{CT}^5 + C T_{CT}^4 + D T_{CT}^3 + E T_{CT}^2 + F T_{CT} + G \]

- \( A = HQ_{CT}^2 + IQ_{CT} + J \)
- \( B = KQ_{CT}^2 + LQ_{CT} + M \)
- \( C = NQ_{CT}^2 + OQ_{CT} + P \)
- \( D = QQ_{CT}^2 + RQ_{CT} + S \)
- \( E = TQ_{CT}^2 + UQ_{CT} + V \)
- \( F = WQ_{CT}^2 + XQ_{CT} + Y \)
- \( G = ZQ_{CT}^2 + aQ_{CT} + b \)
- \( H = cQ_{CT}^2 + dQ_{CT} + e \)
- \( I = fQ_{CT}^2 + gQ_{CT} + h \)
- \( J = iQ_{CT}^2 + jQ_{CT} + k \)

Table 1: Coefficients for fitting ATACOI K508N data.

| \#  | 2.18367E-14 | 10 | -3.24377E-11 | 19 | 1.68872E-06 | 28 | -4.25043E-06 | 37 | 5.61835E-04 | 46 | -3.75058E-02 | 55 | 9.95106E-01 |
|-----|-------------|----|---------------|----|-------------|----|-------------|----|-------------|----|--------------|----|-------------|
| 2  | 5.85583E-12 | 11 | -5.02415E-08 | 20 | 1.76980E-06 | 29 | -3.28026E-04 | 38 | 3.38044E-02 | 47 | -1.84169E+00 | 56 | 4.16888E+01 |
| 3  | -4.48144E-11| 12 | 3.31527E-08  | 21 | -9.56702E-06| 30 | 1.33021E-03  | 39 | -8.48224E-02| 48 | 1.23915E+00  | 57 | 7.21803E+00 |
| 4  | 1.58425E-14 | 13 | -1.39357E-11 | 22 | 4.57327E-09 | 31 | -8.02872E-07 | 40 | 7.59249E-05 | 49 | -3.63177E-03 | 58 | 6.73232E-02 |
| 5  | -1.39483E-13 | 14 | 2.84044E-01  | 23 | 2.59272E-08 | 32 | -1.20476E-05 | 41 | 2.04153E-03 | 50 | -1.56263E-01 | 59 | 4.58484E+00 |
| 6  | 1.75492E-12 | 15 | -1.10117E-07 | 24 | 3.56895E-07 | 33 | -9.20183E-05 | 42 | 1.70517E-02 | 51 | -1.75204E+00 | 60 | 7.39797E+01 |
| 7  | 7.25288E-16 | 16 | -6.09924E-13 | 25 | 2.13087E-10 | 34 | -4.05176E-08 | 43 | 4.54529E-06 | 52 | -2.89699E-04 | 61 | 8.09947E-03 |
| 8  | 3.30571E-14 | 17 | -3.85324E-11 | 26 | 1.73863E-08 | 35 | -3.93049E-06 | 44 | 4.73764E-04 | 53 | -2.93163E-02 | 62 | 7.69465E-01 |
| 9  | 1.04346E-18 | 18 | -9.19179E-10 | 27 | 3.30271E-07 | 36 | -6.30685E-05 | 45 | 6.99700E-03 | 54 | -4.56199E-01 | 63 | 1.78194E+01 |

Figure 3: Measured data and predicted values for ATACOI RICOR K508N.
Error! Reference source not found. shows all of the data collected for the ATACOI cooler with the predicted values for each point overlaid as dotted lines. The method described above predicts the values for this cooler very well. The maximum relative error calculated was 5% which occurred for only a single point. All other relative errors were below 3% and the maximum absolute error in predicted cooler power was 0.25 W. Finally, Equation 1 can be solved for $Q_{CT}$ in terms of $P_{in}$, $T_{CT}$ and $T_{rej}$ to provide an equation for predicting cooling load. These expressions for $P_{in}$ and $Q_{CT}$ can be used in conjunction in a transient thermal model. By alternating between the two equations in each time step an accurate representation of cooler behavior is achieved.

2.3. CIRAS K508N Cooler Performance Testing
The CubeSat Infrared Atmospheric Sounder (CIRAS) project will use two coolers to cool a spectrometer and focal plane independently. Two “flight quality” K508N units were selected by RICOR for their superior thermal and exported force performance. For improved cooling power these coolers were filled to 40 bar and run at 15 V DC using a “high frequency motor” (nominal voltage is 12 VDC). For both of the coolers, thermal performance data was collected similar to the process described in Section 2.2 of this paper. A Ross plot of CIRAS 2 (SN 57-07750) is shown in Error! Reference source not found. 

![Figure 4: Ross Plot of CIRAS 2 data (SN 57-07750)](image)

Error! Reference source not found. shows a comparison of the CIRAS and ATACOI coolers at their nominal input voltage. It shows that the CIRAS coolers are in fact more efficient for a given cooling load. For closed loop control at 20°C reject, 90 K cold tip and with a 0.5 W load, the cooler power necessary for the CIRAS 2 cooler is 8.7 W vs. 11.1 W for the ATACOI cooler corresponding to a 22% reduction in power consumption due to the increased charge pressure and different motor. Furthermore, an easy performance judgement is made at any cooling load by looking at lines of constant specific power. However, it is important to note the unit-to-unit performance variability of K508N units is not well understood. For the K508, the unit-to-unit variability was large. For instance, K508 coolers selected using the process described in Ref. [1] for the CheMin instrument on MSL showed a 9% performance improvement from the worst to the best performing cooler in a lot of six coolers [7].
Figure 5: Ross plot comparing CIRAS 1 (SN 57-07365) and CIRAS 2 (SN 57-07750) coolers to the ATACOI (SN 57-08234) cooler at nominal input voltage levels.

3. Exported Vibration Testing
All the coolers mentioned above were tested for their exported force characteristics at input powers ranging from 4 W to 15 W (or full power). The K508N engineering model cooler for the MASPEX instrument was also tested. The test setup used for these measurements has been described in detail in Refs. [8, 9]. Figure 6 shows the CIRAS 1 cooler bolted to the Kistler model 9255 dynamometer used to measure exported forces. All coolers were run in vacuum enclosure and the reject temperature was not controlled, but did not exceed 30°C during testing. To adjust the input power, the coolers were closed-loop controlled to set points ranging from 90 K to 200 K.

Figure 6: Photograph of CIRAS 1 cooler on dynamometer during test. Vacuum enclosure not shown.

Figure 7 shows the results of the exported forces testing for all coolers. Figure 7a shows the compressor axis force vs. frequency for the ATACOI cooler for various input powers. In addition, harmonics 0 to 4 are marked with different symbols. Figure 7b through Figure 7d show force vs. frequency for harmonics 0 to 4 for each cooler in all three axes. Due to the nature of the K508N assembly, the dominant forces are in the displacer and compressor axis. For all the coolers, at full power, the forces in the compressor axis exceed 100 mN for all of the first 4 harmonics. At higher harmonics the exported forces of the coolers showed less agreement. This could be due to inconsistencies of the displacer rubbing against the inside of the cold finger.
4. Protoqual Thermal Cycling of ATACOI K508N

To advance the flight readiness of the K508N, the ATACOI cooler was taken through protoflight thermal cycling at extreme temperatures. The reject temperature limits were set as close as possible to the operating/non-operating limits of 85°C and -55°C defined by RICOR [10]. Table 2 outlines the limits used during this test. The JPL protoqual temperature test profile consisted of a cumulative 72 hours and three starts at hot op, 24 hours and three starts at cold op, six hours at hot non-op and six hours at cold non-op. Further details on the test profile are contained in Ref. [8]. The cooler performed nominally during the test and showed no sign of degradation or failure. The helium leak rate was measured throughout the test. It showed no dependence on reject temperature and remained at $2 \times 10^{-8}$ Torr L/s throughout the test corresponding to 1.2% drop in charge over 5 years.

Table 2: Temperature limits during protoqual testing and those defined by RICOR.

|                  | Hot Non-Op | Hot Op  | Cold Op | Cold Non-Op |
|------------------|------------|---------|---------|-------------|
| Test Temperatures| 70°C       | 70°C    | -40°C   | -50°C       |
| Hardware Limits  | 85°C       | 85°C    | -40°C   | -55°C       |
5. Vibration Damping Using Mechanical Isolators

The ATACOI cooler was mounted to the dynamometer with three IIT Endine CR3-400 wire rope isolators to test their ability to isolate the vibration output of the cooler from its mounting structure. Figure 8 shows the cooler mounted to the dynamometer with the isolators. The cooler was run open-loop at ambient pressure and data was collected during at the same point in the cool down process. The transmissibility of isolators was defined as the ratio of the force vs. frequency spectrums measured with and without the isolators and has previously been reported in Ref. [11]. The purpose of this test was to validate the previous results in Ref. [11] rather than find a solution for the K508N. Figure 8 shows that the break frequency and roll off presented in Ref. [11] are valid for use with the K508N. There is a large peak in the results for all three axes due to the break frequency of the isolators being near the drive frequency of the cooler. The transmissibility in the vertical axis is artificially high due to there being minimal forces in the vertical axis without the isolators; adding the isolators causes more force to shift into the vertical axis. For the K508N, isolators with a lower break frequency would have to be used in order to sufficiently damp out the drive frequency.

![Figure 8: ATACOI cooler mounted to dynamometer with wire rope isolators (left). Transmissibility of forces in all three axes of cooler (right).](image)

6. Conclusion

Four different RICOR K508N cryocoolers were tested for their thermal performance and exported force characteristics. The results of the ATACOI K508N thermal performance testing were curve fit into an equation which can predict the cooler power to within 5%. The CIRAS coolers which are filled to 40 bar and use a “high frequency motor” can provide 22% reduction in power consumption compared to COTS units for the same cooling conditions. The exported force levels of all the coolers tested are similar for the drive frequency, but tend to deviate more at higher harmonics due to rubbing of the displacer. Wire rope vibration isolators helped damp the vibration levels of the K508N at higher harmonics, but amplified forces near the drive frequency. Finally, protoqual testing on the K508N successfully brought this cooler closer to flight readiness according to JPL flight standards.
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