

Effect of gravity orientation on the thermal performance of Stirling-type pulse tube cryocoolers

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Abstract

The effect of angular orientation on the off-state conduction of pulse tube cryocoolers has been previously explored, as has the effect of orientation on the thermal performance of low-frequency (~2 Hz) GM-style pulse tube refrigerators. The significant effects that have been found are well explained by the presence of free convection that builds up in the hollow pulse tube when the hot end of the pulse tube is not higher than the cold end. This paper extends the investigation of angular orientation effects to the refrigeration performance of high frequency (~40 Hz) Stirling-type pulse tube cryocoolers typical of those used in long-life space applications. Strong orientation effects on the performance of such cryocoolers have recently been observed during system-level testing of both linear and U-tube type pulse tubes. To quantify the angular dependency effects, data have been gathered on both U-tube and linear type pulse tubes of two different manufacturers as a function of orientation angle, cold-tip temperature, and compressor stroke.

Keywords: Pulse tube; Orientation dependence; Convection; Angular dependency

Introduction

During the past year, several instances of fairly strong gravity-orientation dependent performance have been noted during ground testing of high-frequency Stirling-type pulse tube cryocoolers. In two cases the level of effect was large enough to prevent meeting system operational requirements during ground testing when the hot end of the pulse tube was not in an upward orientation. The effect was noted in tests involving both U-tube and linear pulse tube configurations built by two different manufacturers. All of the applications involved the use of classic Oxford-type linear compressors with drive frequencies in the 30 to 60 Hz range. Previously, gravity orientation dependence has been reported for pulse tubes driven at low frequency (~2 Hz) using Gifford-McMahon compressors.¹ However, high frequency pulse tubes have often been thought of as free of any strong gravity orientation dependence.

Figure 1 schematically illustrates the two common pulse tube configurations: the linear and U-tube. Each traditionally involves a screen-filled regenerator mated to an adjoining open pulse tube. With the linear configuration, the regenerator and open pulse tube are arranged end-to-end on a common axis; with the U-tube, the open pulse tube is folded back parallel to the regenerator. In addition to the obvious difference in physical layout, one practical consideration is that the pulse tube and regenerator are often made the same length in the U-tube design, whereas the linear con-

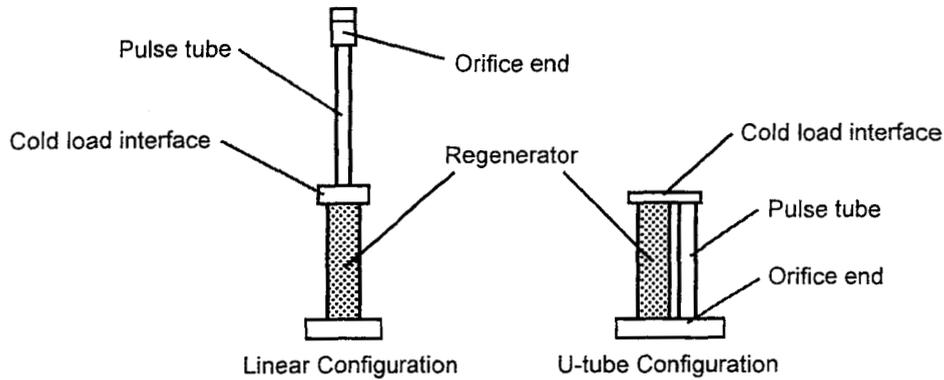


Figure 1. Leading pulse tube construction configurations.

figuration is not constrained by this consideration. As a result, the open pulse tube of a U-tube design often has a lower length/diameter ratio than that of a linear design.

The basic physics behind the gravity dependence is understood as free convection within the open pulse tube. This convection is driven by the strong end-to-end temperature gradient within the open tube that varies from near room temperature at the orifice end, to the cooler's cryogenic operating temperature at the regenerator end. The regenerator itself has been found to be relatively immune to convection effects because of its dense filling with screens and particles.

The thermal loads associated with free convection within a non-operating cooler have also been well characterized in previous studies.² Off-state conduction enhanced by convection is particularly important when a primary cooler is operated in parallel with a non-operating backup cooler. In this case, the convective load in the 'off cooler' is a significant load on the operating cooler. Figure 2 presents representative data for the angular dependency found for this 'off-state' convective load.²

To quantify the recently observed orientation effects with high-frequency Stirling-type pulse tube cryocoolers, a series of detailed tests have been conducted to generate performance data on both U-tube and linear type pulse tubes of two different manufacturers as a function of orientation angle and cold-tip temperature. The following sections discuss both the orientation effects observed during cryogenic system-level testing and the detailed results of these parametric pulse tube measurements.

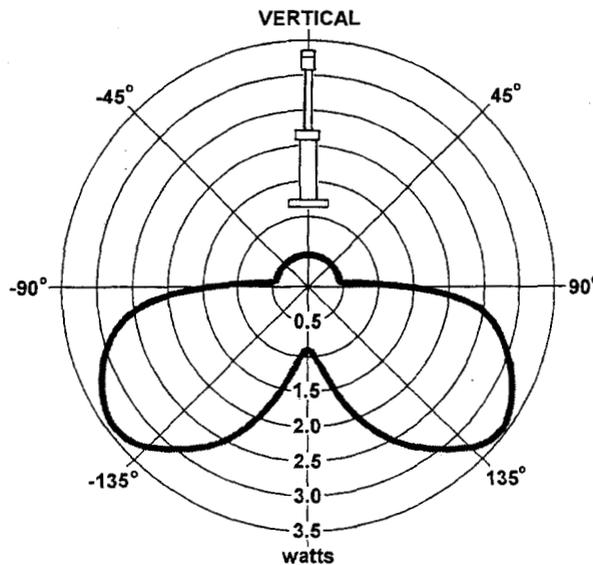


Figure 2. Conduction load of a non-operating linear pulse tube as a function of orientation angle with respect to gravity.

Cooler System Test Observations

In spacecraft and instrument system-level testing, often the cryocooler gravity orientation is constrained by the requirements of the overall test setup and the test facility. In addition, the orientation will often be different in tests conducted at the instrument level as opposed to at the spacecraft level. If a cryocooler has a gravity orientation dependence, it often shows up when attempting to correlate cooler performance data taken at the cooler level, instrument level, and spacecraft level.

Experience with pulse tube cryocoolers in various system test sequences is described below. These examples provide a summary of the types of issues raised in testing.

Atmospheric Infrared Sounder (AIRS) instrument

JPL's Atmospheric Infrared Sounder (AIRS) instrument was launched in May 2002 on NASA's Earth Observing System Aqua platform. Its mission is to measure the atmospheric air temperature using a HgCdTe focal plane cooled to 58 K by a redundant pair of 55 K TRW pulse tube coolers.^{3,4} As shown in Fig. 3, the AIRS flight pulse tube coolers are of the linear type, with the pulse tubes of the primary and redundant cooler mounted side-by-side, but facing in opposite directions. Thus, gravity has two possible effects: 1) on the operating cooler, and 2) on the off-state conduction of the non-operating, standby cooler. If possible, during cooler testing the 'off-cooler' pulse tube was positioned vertically upward as defined in Fig. 2 to minimize convection enhanced off-state conduction. This led to the operating pulse tube positioned in the inverse (hot end down) 180° orientation. In addition, during instrument-level and spacecraft-level testing, both pulse tubes were often operated in a horizontal orientation, where convection effects can also be quite strong. The variable load caused by the various orientations of the off cooler were successfully managed through the application of special test and data reduction techniques.⁵ However, during the multi-year test sequence involving operation at 0°, 90° and 180°, no noticeable gravity orientation dependence was observed in the operating cooler.

TES Cooler Development

The EOS Tropospheric Emission Spectrometer (TES) instrument is an infrared instrument designed to measure the state of the Earth's troposphere. TES uses two 57 K TRW (now NGST) pulse tube coolers to cool two separate focal planes to 62 K. As shown in Fig. 4, the two coolers are a variant of the TRW AIRS pulse tube cooler, but with the linear-style pulse tube hard mounted to the compressor.^{6,7} The TES instrument completed instrument level testing in spring 2003, and will

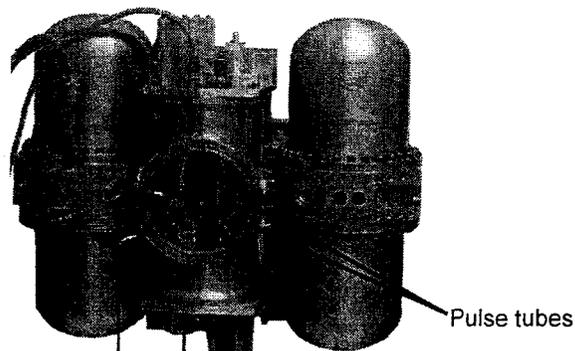


Figure 3. AIRS EM cooler system.

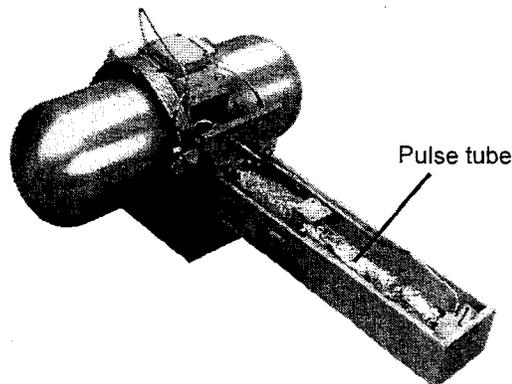


Figure 4. TES cooler system.

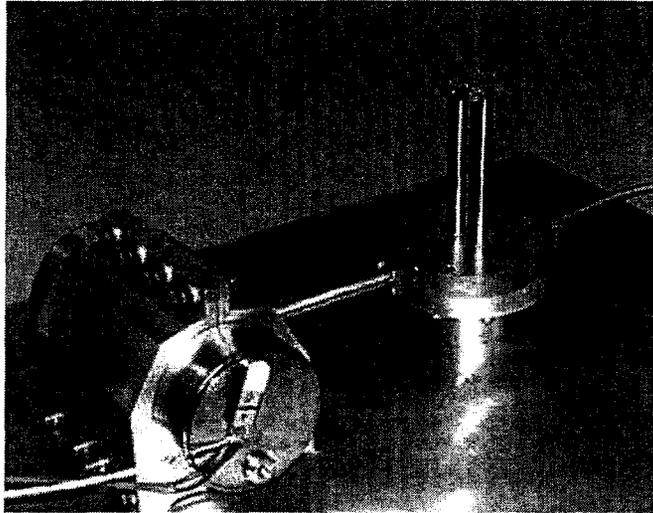


Figure 5. Gamma-ray cooler system.

complete spacecraft-level testing in the fall of 2003; it is scheduled for launch aboard NASA's Aura spacecraft in early 2004.

Within TES, the coolers are positioned as shown in Fig. 4, with the pulse tubes pointing down at a 125° angle from the instrument's nadir pointing face. During instrument-level testing, the nadir face was facing up, causing the linear pulse tubes to be in a worst-case attitude for convection effects.

During early ground testing of the instrument's cryogenic assemblies alone, no gravity attitude effects were observed.⁷ However, during instrument-level testing—which used the same pulse tube orientation—significant attitude orientation effects were discovered. The noted effect was that the instrument cryogenic load appeared higher than expected by about ~ 110 mW on Cooler A and ~ 310 mW on Cooler B. In addition, Cooler B exhibited a chaotic load behavior well explained by a buoyancy flow phenomena.

When gravity orientation was suspected as a possible cause, a test was run whereby the cooler cryogenic loads were increased by nearly 100% using the built-in focal-plane decontamination heaters. The idea behind this was to force the coolers to work harder in order to break up any free convection cells within the pulse tube. The data clearly showed that the buoyancy induced flow phenomena disappeared at the higher stroke level. In addition, the expected coldblock temperature control response returned, and the instrument load on the two coolers matched predictions within 30 mW.

Gamma-ray cooler testing

In the 2000 timeframe, JPL contracted with Lockheed Martin ATC to build a low cost pulse tube of the U-tube configuration to be driven by a tactical Stirling cooler compressor.⁸ The successful new cooler achieved over 1.6 watts of cooling at 80 K at 23 W/W, and had the advantage of greatly reduced vibration at the coldtip and no life-limiting moving cold elements. However, the cooler also displayed a strong gravity orientation dependence. During recent system-level testing of the cooler with a gamma-ray detector, this orientation sensitivity required that the entire test facility be operated upside down. With the cooler cold tip vertically upward, which places the hot end of the pulse tube at the bottom, the cooler was unable to reach a no-load temperature below 110 K. In contrast, with the cold tip facing down, the cooler achieved a no-load temperature of 45 K, with plenty of capacity at 80 K to cool the gamma-ray detector.

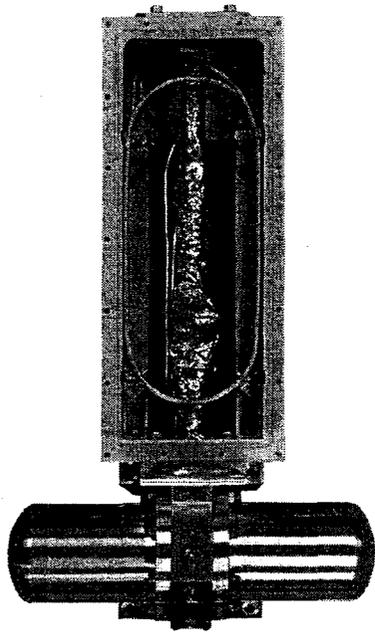


Figure 6. IMAS Engineering model cooler No. 101.



Figure 7. Cooler test facility allowing operation at various angles with respect to gravity.

Characterization of pulse tube orientation dependence

To understand and quantify the pulse tube orientation dependence noted in the above system-level tests, a special test program was undertaken at JPL using both the gamma-ray U-tube pulse tube cooler shown in Fig. 5, and an IMAS linear pulse tube cooler, shown in Figure 6. The IMAS cooler^{9,10} was built by TRW (now NGST) for JPL in 1998 and uses a pulse tube very similar to the one used on AIRS and TES.

To capture the orientation dependence data, a special rotating test facility, shown in Fig. 7, was used. It allows the pulse tube cooler to be adjusted to any angle with respect to gravity, and provides precise control of the cooler heatsink temperature via a temperature-controlled fluid loop.

U-tube cooler orientation dependence

Figure 8 shows the measured dependence of the gamma-ray cooler no-load temperature on inclination angle with respect to gravity. These data were acquired with the cooler operating near maximum power with a drive frequency of 40 Hz. Note that the curve shape on this polar plot is very similar to that for the linear pulse tube off-state conduction shown earlier in Fig. 2.

To explore possible dependency of the convection effects on operating temperature, data were also taken with various heater loads applied to the cooler coldtip. Figure 9 displays the very similar performance achieved at the various heater-load levels and operating temperatures.

Linear pulse tube cooler orientation dependence

Figure 10 shows the less strong dependence of the IMAS cooler no-load temperature on inclination angle with respect to gravity. As with the gamma-ray cooler, these data were acquired with the cooler operating near maximum power, but with a drive frequency of around 60 Hz. Note that the curve shape on this polar plot is again similar to that for the convection-driven off-state conduction shown earlier in Fig. 2, but with a much less pronounced angular dependence.

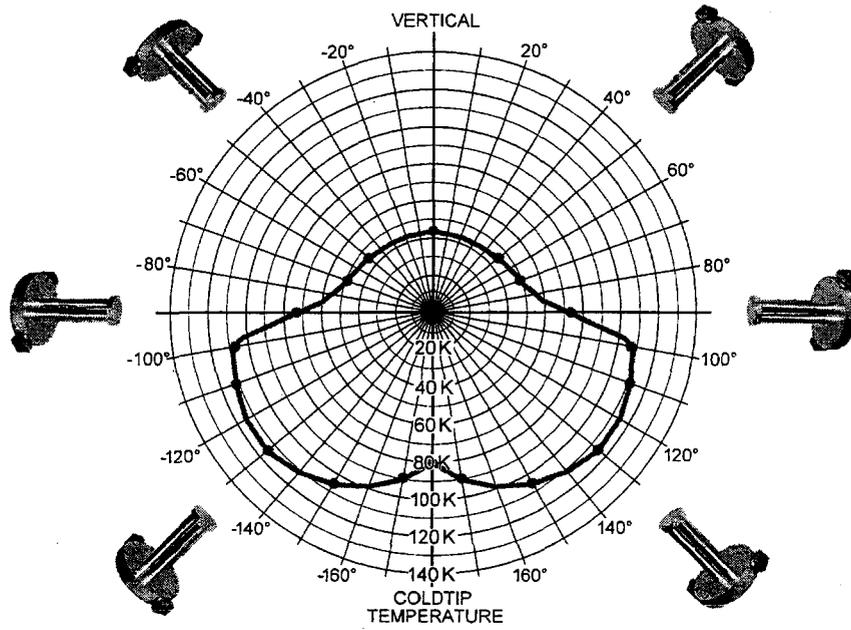


Figure 8. Dependence of no-load temperature on inclination angle for gamma-ray U-tube type pulse tube cooler.

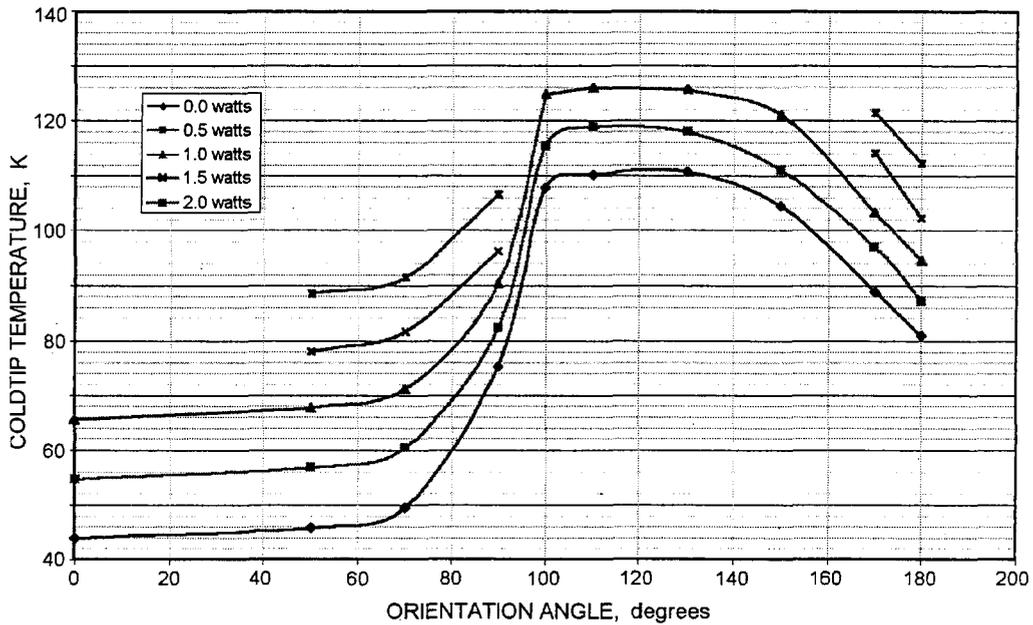


Figure 9. Dependence of operating temperature on inclination angle for gamma-ray U-tube type pulse tube cooler with various heater loads applied to the coldtip.

To explore an expected dependency on pressure wave amplitude within the pulse tube, data were also taken with various power levels applied to the compressor. Figure 11 displays the performance achieved at the various power levels.

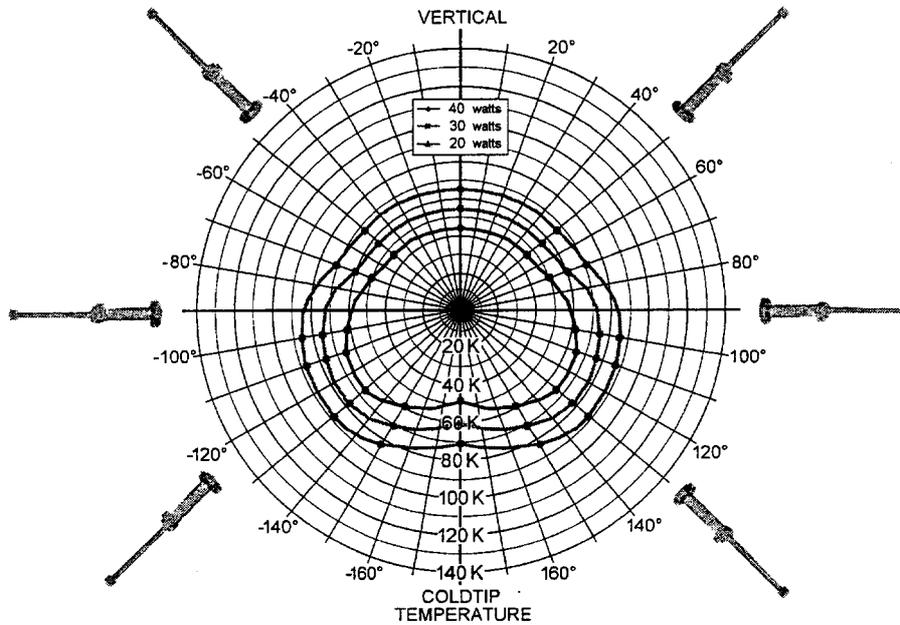


Figure 10. Dependence of no-load temperature on inclination angle for IMAS linear-type pulse tube cooler.

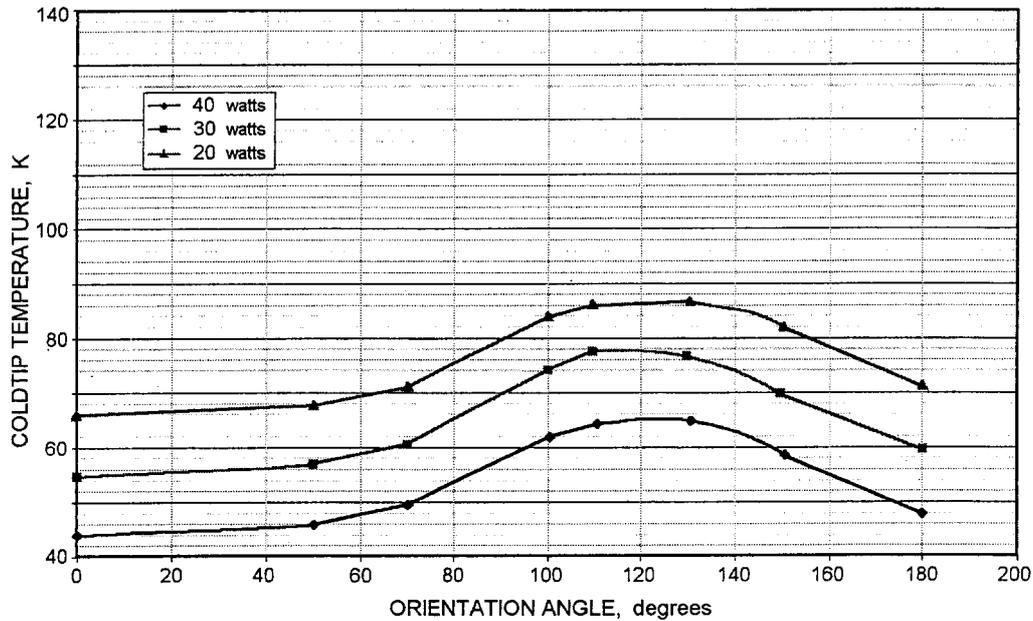


Figure 11. Dependence of operating temperature on inclination angle for IMAS linear-type pulse tube cooler as a function of compressor input power level.

Summary

The effect of angular orientation on the off-state conduction of pulse tube cryocoolers has been previously explored, as has the effect of orientation on the thermal performance of low-frequency (~ 2 Hz) GM-style pulse tube refrigerators. This paper has extended the investigation of angular orientation effects to the refrigeration performance of high frequency (30-60 Hz) Stirling-type pulse tube cryocoolers typical of those used in long-life space missions. Strong orientation effects on the performance of some pulse tube cryocoolers of this type have been recently observed during system-

level testing. However, other very similar space pulse tube coolers, such as the AIRS coolers, have not displayed significant gravity orientation effects.

To help quantify the angular dependency phenomena, this study has acquired data on both U-tube and linear-type pulse tubes. The data agree well with the orientation dependence observed at the system-level and the general angular dependence expected for convection processes. However, the significant difference observed between similar pulse tube constructions suggests that there are additional important variables that need to be identified. A key conclusion is that additional research is needed to identify the critical design drivers and to develop pulse tube designs that minimize convective effects in future space coolers.

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