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Performance Comparison of In-Line and Coaxial Stirling Pulse Tube Cryocoolers for Spaceflight Applications

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Abstract. Cryocoolers are utilized in space missions to enable the operation of sensitive detectors at cryogenic temperatures. An enhanced cryocooler design optimized for spaceflight purposes, the Stirling pulse tube cryocooler (SPTC), offer a hybrid architecture that combines the high thermodynamic efficiency of Stirling systems with the low mechanical vibrations of pulse tubes. This work provides a comparative evaluation of two SPTC configurations; in-line and coaxial; with a focus on spaceflight applicability. We analyze thermodynamic performance, spacecraft integration trade-offs, and the alignment of each configuration with heritage technologies, concluding that coaxial SPTC systems represent a compelling next-generation choice for spaceflight cryocooling.

1. Introduction

The successful deployment of cryogenic instrumentation in space-based observatories is critical to enable high-precision, low-noise measurements. Cooling of instruments to cryogenic temperatures significantly suppresses thermal background noise and enhances the detector signal-to-noise ratio. This can be crucial for a range of detectors utilized across the electromagnetic spectrum, from X-ray to radio wave [1]. Moreover, the exploitation of superconducting devices and electronics necessitates cryocooling [2]. In some cases, infrared telescopes as a whole may require cryocooling to ensure sensitivity to impingent flux in the infrared spectrum.

Stirling cryocoolers have historically been favored for space applications due to their compactness, relatively high coefficient of performance (COP), and proven heritage flight record [2]. However, a known limitation of traditional Stirling systems is their mechanically active cold ends, which introduce vibrations into the detectors or focal plane assemblies. These can adversely affect the performance of ultra-sensitive instruments such as interferometers and bolometers. Pulse tubes are favorable from a vibration perspective as they have no moving parts at the cold end, however, they are much less efficient than Stirling systems and less favorable for spaceflight due to orientation requirements [3].

To overcome this, a hybrid system known as the Stirling Pulse Tube Cryocoolers (SPTCs), has been developed. SPTCs integrate a Stirling compressor with a pulse tube and a warm end displacer. When the warm end displacer is run passively, it removes moving components from the cold end, minimizing mechanical disturbances while preserving Stirling efficiencies [4]. This hybridization can be achieved with a range of layouts and configurations. In this study, the two configurations of the SPTC, in-line and coaxial, are compared while all other components are kept as constant and identical as possible. The in-line configuration refers to the regenerator and pulse tube being linearly aligned, with the pulse tube connected directly above the regenerator. In the coaxial configuration, the pulse tube is contained concentrically within the regenerator and flow reversal occurs at the cold end [5]. We assess their thermodynamic efficiency, mechanical complexity, integration challenges, and performance in experimental settings. We further relate these findings to their potential application in space missions, especially those demanding miniaturization, low power, and high reliability.

2. Governing Principles and System Equations

The operation of a cryocooler is based on the periodic compression and expansion of a working gas, typically helium. For the Stirling cycle, the idealized COP is defined by:

$$\mathrm{COP}_{\mathrm{ideal}} = \frac{T_C}{T_H - T_C}, \tag{1}$$

where T_C and T_H are the cold and hot temperatures, respectively.

In an SPTC, the working gas is displaced sinusoidally, generating pressure oscillations and enthalpy flow in the regenerator and pulse tube [6]. For an ideal regenerator, the net refrigeration effect Q_c is related to the enthalpy flux $\dot{H}$ at the cold end:

$$Q_c = \frac{1}{\tau}\int_0^{\tau} \dot{H}(t)\, dt, \tag{2}$$

where τ is the period of oscillation.

The enthalpy flow in the pulse tube is given by:

$$\dot{H} = \rho \cdot U \cdot h, \tag{3}$$

where ρ is the gas density, U is the volumetric flow rate, and h is the specific enthalpy.

Loss mechanisms include regenerator inefficiency, pressure drop, acoustic streaming, and thermal conduction. These are collectively captured in the non-ideal COP:

$$\mathrm{COP}_{\mathrm{actual}} = \eta \cdot \mathrm{COP}_{\mathrm{ideal}},$$

where η accounts for practical inefficiencies and typically ranges from 0.1 to 0.3 for space-qualified units [7, 8, 9].

3. System Architecture and Thermal Design

3.1. In-Line Configuration

In-line SPTCs feature a linear arrangement of the dual-opposed compressors, regenerator, and pulse tube. The warm end displacer then loops back into the system at the warm end. This simple linear geometry in the regenerator, pulse tube, and at the cold head promotes predictable gas dynamics and minimal fluid friction. However, the cold head is axially sandwiched between components, limiting accessibility for integrating detectors and focal plane assemblies for cooling, and increasing the number of thermal linkages required which adds to the complexity and thermal losses throughout the system. This results in an increased power input needed to drive the SPTC to produce the necessary amount of heat lift to mitigate the actual heat load at the cryocooled surface for the correct cryogenic temperature. Figure 1 shows a schematic of the in-line configuration SPTC on the left.

3.2. Coaxial Configuration

Coaxial systems wrap the regenerator concentrically around the pulse tube, producing a more compact assembly. This geometry reduces the overall volume of the full SPTC system and permits easier integration into spacecraft payloads. Additionally, it offers a fully exposed cold end, which is a particular advantage coupling to focal plane arrays or the detector surface of interest, reducing intermediary thermal linkage and minimizing additional power input required into the SPTC compressors to mitigate thermal losses.

Nevertheless, coaxial arrangements may introduce radial temperature gradients and losses due flow mixing at the coaxial cold head. Research has shown this is difficult to adequately characterize [4]. Figure 1 shows a schematic of the coaxial configuration SPTC on the right.

4. Experimental Results

Recent SPTC designs have achieved cooling powers ranging from 0.5 W to 7.5 W at 80 K [7, 4]. These results confirm the scalability of both in-line and coaxial designs across a variety of thermal loads. The Oxford University prototypes yielded approximately 2.5 W of cooling at 80 K with 80 W input power [6].

Japanese space-qualified coaxial designs achieved 2–3.4 W at 77 K with 100 W input, demonstrating reliable long-duration performance in simulated space conditions. These systems used high-pressure helium (∼2.5 MPa) and operated around 60 Hz [1].

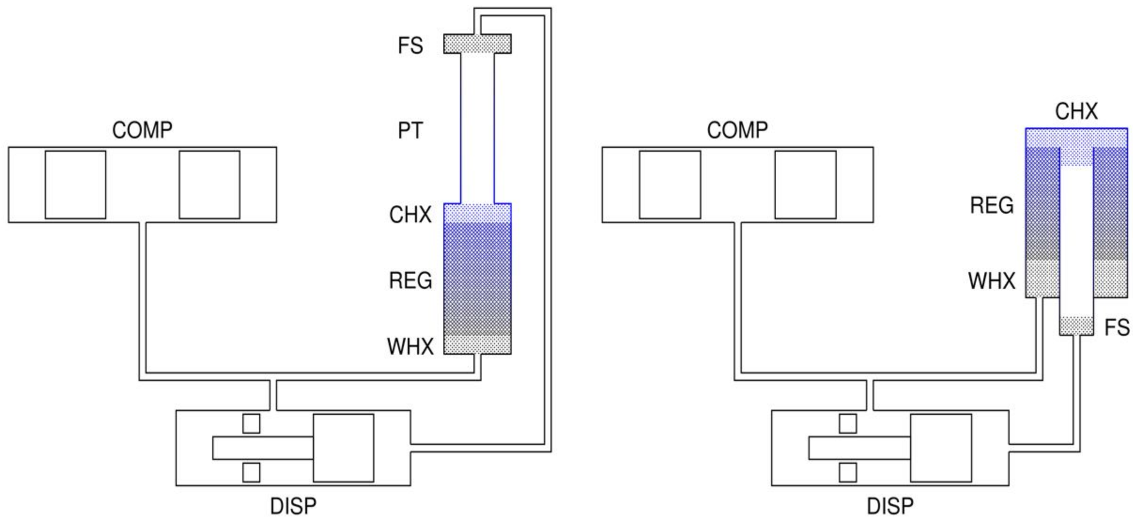

Figure 1. Schematic of Stirling pulse tube cryocoolers with warm end displacers in an in-line configuration (left) and coaxial configuration (right). Reproduced from [4]. COMP is the compressor, DISP is the displacer, FS is the flow straightener, PT is the pulse tube, CHX is the cold head heat exchanger, REG is the regenerator, WHX is the warm end heat exchanger.

Studies have revealed that in-line cryocoolers are more sensitive to gravitational orientation, due to vertical stratification in the pulse tube [8]. In contrast, coaxial geometries maintained stable output irrespective of orientation, supporting their viability in free-floating spacecraft [7].

High-frequency coaxial systems employing inertance tubes and double-inlet orifices have demonstrated COP_{actual} values up to 0.24, closely approaching the upper limits of single-stage cryogenic cooling efficiency [9]. These results underscore the value of phase-tuned flow control mechanisms for performance enhancement.

5. Discussion

5.1. Comparison of Configurations

In-line SPTCs are relatively easier to design and model. Their linear configuration ensures straightforward mechanical coupling and minimal parasitic losses. However, they suffer from bulky packaging, poor accessibility to the cold end, and reduced flexibility in focal plane integration.

Coaxial SPTCs, though slightly more complex to design, offer compactness and superior payload interfacing. They mitigate gravitational sensitivity, reduce vibrations, and offer better packaging density. Despite minor losses due to radial flow asymmetries, performance remains competitive and continues to improve with refined inertance design.

Table 1: Comparison of In-line vs. Coaxial SPTCs

Property	In-line	Coaxial
Integration ease	Low	High
Mechanical complexity	Low	Medium
Cold head exposure	Poor	Excellent
Efficiency (actual)	Slightly higher	Slightly lower

5.2. Spaceflight Implementations

While Stirling and pulse tube cryocoolers have a demonstrated flight heritage, SPTCs have yet to be flown. Their compact form factor and thermodynamic efficiency position them as strong candidates for future spaceflight missions. Existing space missions highlight the performance advantages of Stirling and pulse tube systems: (1) Sentinel-3's SLSTR instrument uses a dual-opposed Stirling cryocooler for vibration cancellation and redundancy, demonstrating robust operational maturity [10]. (2) The Japanese AKARI infrared telescope utilized a hybrid cooling system—liquid helium supplemented with a two-stage Stirling mechanical cryocooler—to extend mission lifetime through efficient cryogen management [11]. (3) NASA's AIRS instrument onboard Aqua employs a fully redundant two-stage pulse tube cryocooler assembly, marking the first use of pulse tube technology in orbit and providing stable low-noise cooling for Earth observations [12].

5.3. Optimization Pathways

Recent advances in additive manufacturing have enabled internal geometries with optimized inertance paths, lower thermal conductivity, and tailored regenerator porosity [13]. Multi-material printing techniques allow integrating compliant supports with high-conductance channels, further enhancing structural and thermal performance [13]. Machine learning algorithms are being explored to design optimized flow networks, predict failure, and autonomously calibrate drive frequencies for peak COP under varying thermal loads [14, 15]. Cascaded hybrid cooling strategies that precool with Stirling and pulse tube cryocoolers, and integrate Joule–Thomson or sorption stages, have been flown in space and continue to be under development for missions demanding temperatures below 10 K, such as quantum optics or superconducting detector arrays [16, 17].

6. Conclusion

This study has presented a comparative evaluation of in-line and coaxial Stirling pulse tube cryocoolers (SPTCs) with a focus on their suitability for spaceflight applications. While both configurations demonstrate effective cooling performance at cryogenic temperatures, the coaxial design offers significant advantages in system compactness, payload integration, and orientation insensitivity. Experimental results indicate that with further refinement, coaxial systems can match or exceed the thermodynamic performance of in-line counterparts while providing superior mechanical and thermal integration with spacecraft instruments. Although SPTCs have not yet flown, their hybrid efficiency and vibration-free cold ends make them strong candidates for next-generation missions, where their constituent cryocooling components have significant spaceflight heritage. A brief overview of varying spaceflight integrations and tangential needs is also addressed. Continued optimization, particularly in phase tuning, additive manufacturing, and smart control algorithms, will be critical to closing remaining performance gaps. These findings support the advancement of coaxial SPTCs as a viable and promising solution for future cryogenic spaceflight technologies.

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