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A NON-TUBE INERTANCE DEVICE FOR PULSE TUBE CRYOCOOLERS

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ABSTRACT

Inertance Pulse Tube Cryocoolers make use of a long tube for phase shifting and optimization of performance. This long tube presents a challenge for packaging in most applications, and is also a concern for environments where vibration is present (e.g., launch). In the present invention, a gap configuration is used in place of the tube, resulting in a more compact inertance device. Using the SAGE software, the performance of this new device is found to be comparable to that of an inertance tube. Significantly, this new invention offers the flexibility to change the inertance value during testing and operation, which cannot be done with the tube configuration.

KEYWORDS: Pulse Tube, Cryocoolers, Inertance Tube, Phase Shift Devices.

INTRODUCTION

In recent years, there has been tremendous interest in pulse tube (PT) cryocoolers because of their reliability (no cold moving parts) and high efficiency (some of the best efficiencies match that of Stirling coolers). PT cryocoolers are also rapidly replacing other mechanical coolers in the field (e.g., Stirling, and Gifford-McMahon). However, the most efficient PT cryocooler in the industry to date consists of a long inertance tube (up to several meters in length) between the warm end of the pulse tube and a buffer volume. This long inertance tube presents a challenge for packaging in most applications, and is also a concern for environments where vibration is present (e.g., launch environment). In the present invention, a pulse tube with a compact inertance gap is proposed (several inches long instead of meters). A PT with inertance gap (US Patent # 20090084114, [1]) offers comparable performance to a PT with the long inertance tube, but is much more compact, easier to package, avoids launch vibration issues and offers real-time performance optimization capability.

LRC ANALYSIS

One can analyze the phase shift mechanism using an LRC circuit analogy. The inductance, L (an analog to the flow inertance term), resistance, R (an analog to the flow impedance), and the capacitance, C (an analog to the fluid heat capacity term) of a tube geometry can be written as follows [2]:

$$L=4\, l_t / (\pi\, d^2); \quad (1a)$$
$$R=128\, l_t\, \eta / (\pi\, \rho\, d^4); \quad (1b)$$
$$C=M\, v / (\gamma\, R\, T) \quad (1c)$$

where, l_t, d and v are the length, diameter and internal volume of the inertance tube, η, ρ and γ are viscosity, density and specific heats ratio. According to the Eq. (1a), there are two ways one can add inductance (or inertance): by increasing l_t or decreasing d. Since resistance is inversely proportional to the fourth power of d, decreasing d will increase resistance substantially. Thus the best way to add inertance in a tube geometry is to add length, resulting in a long and slender tube.

With the present invention, the inductance, resistance and capacitance of a gap geometry can be written as

$$L=l_g / (w\, s); \quad (2a)$$
$$R=12\, l_g\, \eta / (\rho\, w\, s^3); \quad (2b)$$
$$C=M\, v / (\gamma\, R\, T) \quad (2c)$$

where l_g, w, s and v are the length, width, thickness and internal volume of the gap. Equating Eqs. (1a) and (2a), one gets

$$l_g = (4\, w / \pi)\, (s / d^2)\, l_t \quad (3)$$

From Eq. (3), one sees that the length of the inertance gap (l_g) is orders of magnitude (s/d^2) smaller than the length of the inertance tube (l_t). (Note that for a given w, S is ~ 1*E-05 m and d is ~1*E-02 m.)

In the present invention, a gap is placed between the warm end of the pulse tube and the buffer (surge) volume (or reservoir) in place of the inertance tube.

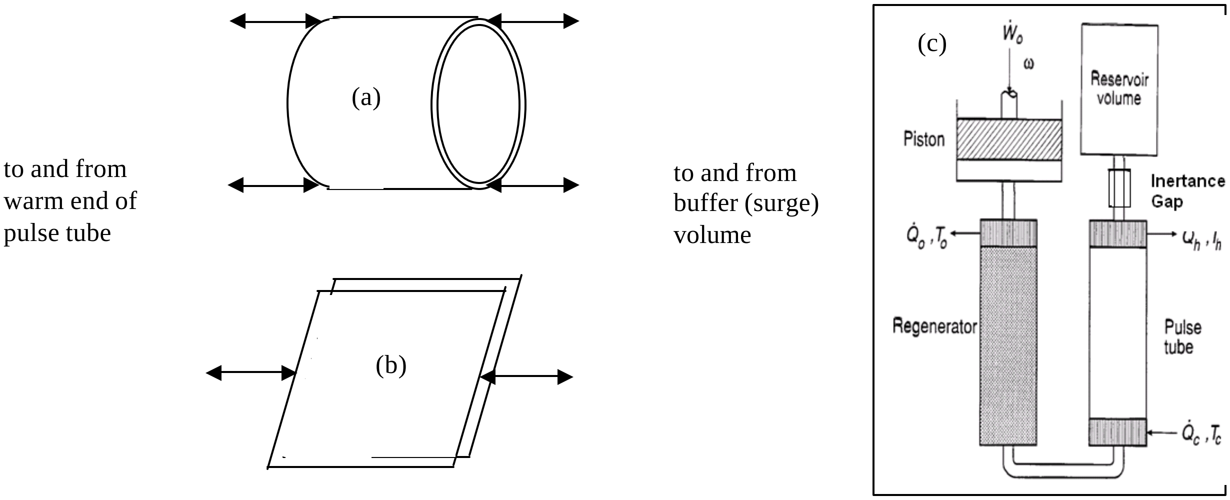


FIGURE 1. Inertance Gap configuration (a) a concentric inertance gap, (b) an inertance gap between plates, and (c) a pulse tube with an inertance gap.

PULSE TUBE MODEL

The inertance gap can be either of concentric (FIGURE 1a) or parallel plate (FIGURE 1b) configuration. The concept was then verified by the SAGE model [3]. TABLE 1 lists the dimensions of the pulse tube cryocooler studied. TABLE 2 shows the difference in dimensions between the inertance tube configuration and that of an inertance gap. The fill pressure of the cryocooler is 1.6 MPa, and the frequency of operation is optimized between 7.5 Hz and 2.3 Hz.

FIGURE 2 shows the performance of an inertance PT versus that of an inertance gap as predicted by SAGE [3] at 80 K cold tip temperature. The cooling capacity of the cooler is plotted on the x-axis, where as the corresponding total input power is plotted on the y-axis. A concentric gap was assumed in the study, with the maximum diameter of the gap equal to the diameter of the pulse tube. Both the frequency of operation and the inertance geometry of the tube and the gap are optimized during the runs. As one can see, the performance of the inertance gap PT is more efficient than that of the inertance tube PT, especially at high powers. Moreover, the design of the inertance gap is far more compact (inches in length) than that of the inertance tube (a few meters in length). Dimensions of the inertance tube and that of the gap for the runs are compared in TABLE 2.

TABLE 1. Dimensions of the pulse tube cryocoolers.

Parameter	Pulse Tube Dimensions
Compressor Piston Area	4.56 E-03 m^2
Regenerator Length	0.208 m
Regenerator Diameter	0.0395 m
Pulse Tube Length	0.203 m
Pulse Tube Diameter	0.0254 m
Surge Volume	2.85 E-04 m^3

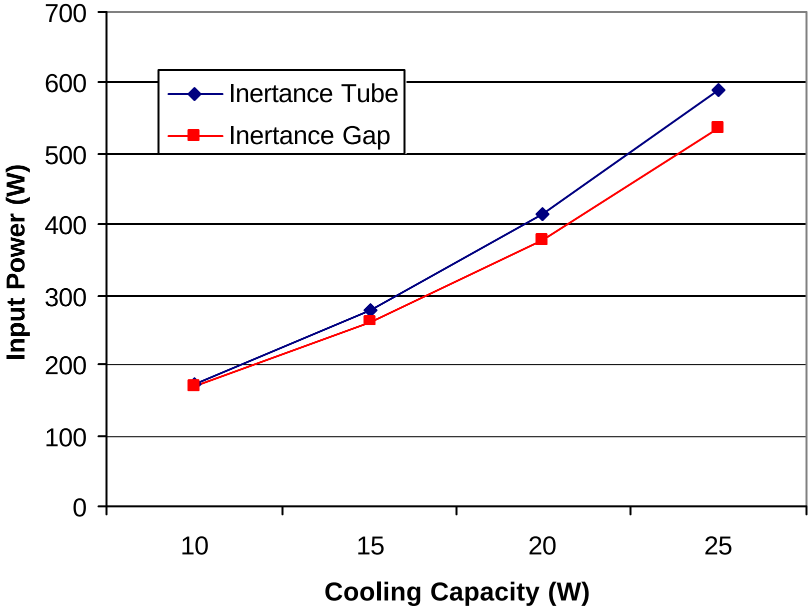


FIGURE 2. Comparison of pulse tube performance between an inertance gap and an inertance tube.

TABLE 2. Comparison of inertance tube dimensions to that of gap for FIGURE 2.

	Inertance Tube		**Inertance Gap**	
Cooling	**Length**	**Diameter**	**Length**	**Gap**
10 W	1.262 m	1.673 mm	0.01 m	26.2 micron
15 W	1.925 m	2.093 mm	0.0268 m	41.0 micron
20 W	2.445 m	2.447 mm	0.0482 m	55.1 micron
25 W	2.919 m	2.784 mm	0.0695 m	68.1 micron

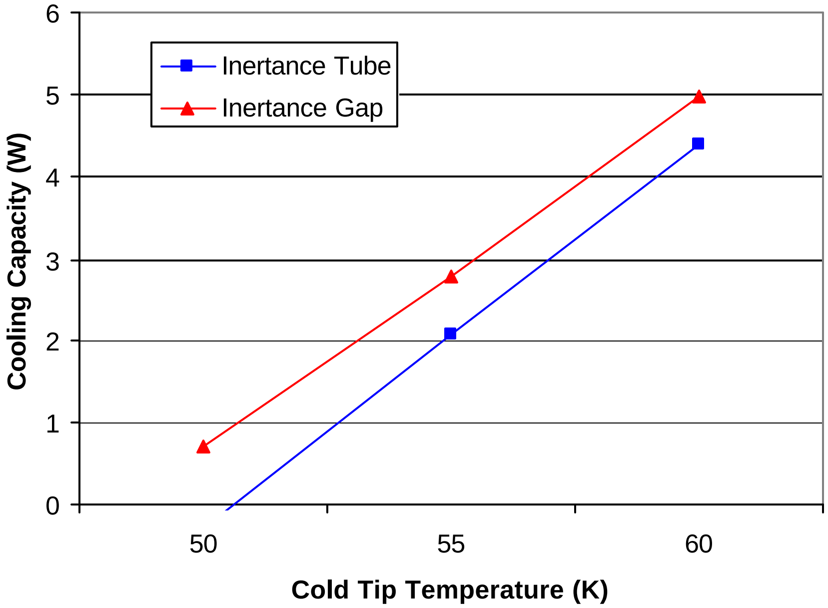
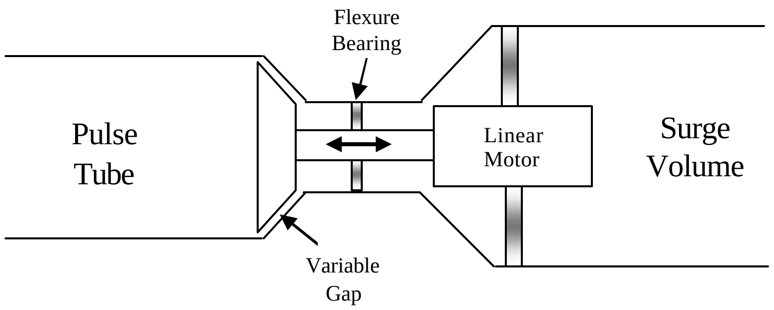


FIGURE 3. Cooling capacity as a function of cold tip temperature

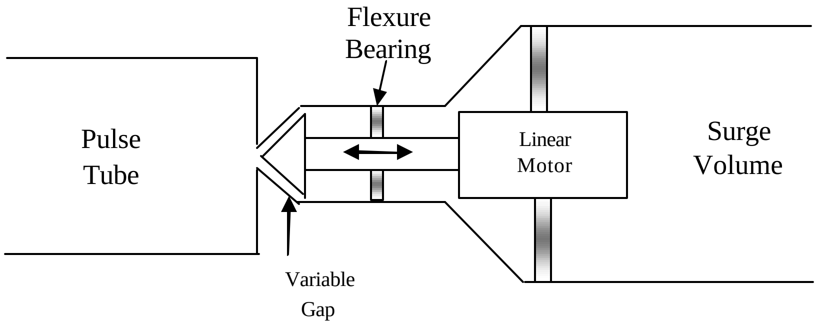
FIGURE 3 show the cooling load as a function of the cold tip temperature for both the inertance tube and gap configurations. As one can see, the inertance gap pulse tube clearly out-performs that of the inertance tube.

VARIATION OF THE INERTANCE GAP

One major advantage of the inertance gap is the capability to vary the inertance gap. With inertance tubes, pulse tube coolers optimized for a particular operating condition cannot be optimized for another operating condition by changing the inertance tube geometry. With the inertance gap approach, the width of the gap can be varied as shown in FIGURE 4.



(a) Variable Gap Opening



(b) Variable Gap Opening

FIGURE 4. Gap size variation methods.

FIGURE 5 shows the capability of the inertance gap to alter the performance of the pulse tube cryocooler for a constant input power of 300 W. Whereas the performance of the inertance-tube PT is fixed for a particular cold tip temperature (due to the fixed geometry of the inertance tube), the performance of the inertance-gap PT changes by 43% at 70 K and 33% at 55 K by decreasing the inertance gap from 47.5 micron to 40 micron.

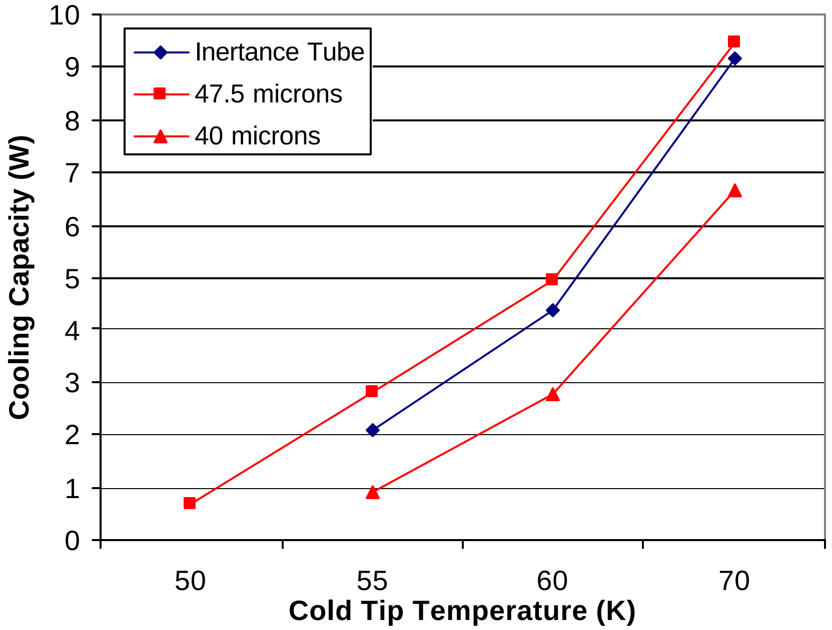


FIGURE 5. Pulse tube performance variation versus inertance gap size.

CONCLUSIONS

The concept of using a gap geometry for PT phase shifting in place of the tube geometry has been presented in this paper. The inertance gap appears to out-perform the tube geometry, possibly due to lower pressure drop in the gap geometry (which can be approximated by that of parallel plates, [4]). Variation of cooling load by controlling the inertance gap width has also been shown in this paper.

For future work, the application of the inertance gap to pulse tubes of different sizes and operating conditions will be explored. Measurement of the oscillatory pressure drop across the inertance gap is part of an on-going IR&D effort at the Aerospace Corporation.

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