Optimization of Phase Controller for Pulse Tube Cryocooler

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ABSTRACT

The development of pulse tube cryocoolers has increased rapidly because of its mechanical simplicity and high reliability due to the absence of moving parts in the cold region. Pulse tube cryocoolers are suitable for cooling of infrared sensors, low noise electronic applications, liquefaction of gases, etc. A Pulse Tube Cryocooler performance depends on the phase controller. The phase controller used here is inertance tube-bounce space. The phase difference between the compressor and bounce space flow is around 180º. If this phase difference is utilized, the inertance tube-bounce space combination can act as a compact phase controller. This paper aims to optimize the dimensions of the inertance tube, bounce space, regenerator and frequency for the best performance of our pulse tube cryocooler. A Stirling pulse tube cryocooler's performance is maximum when the pressure and mass flow are in phase at the midpoint of the regenerator. To achieve this phase shift, the pressure should lag the mass in acceptor. A cryocooler system was designed using Sage V11 software, for the simulation and optimization. The maximum power input to the cryocooler was limited to 100 W. This model was used to maximize the cooling effect for the highest COP. The COP of the optimized cryocooler was found to be 0.043, which is 16.12% of the Ideal COP of pulse tube cryocoolers.

INTRODUCTION

Cryocoolers are capable of attaining cryogenic temperature with the help of gas cycles. They are used for the cooling of superconducting devices, infrared sensors, and liquefaction of gases. Stirling cycle is the gas cycle responsible for cooling in the regenerative type cryocoolers. Pulse tube cryocooler is a regenerative type cryocooler that works on Stirling cycle. These cryocoolers were introduced in the early 1960's. They were an attraction because of the advantages of mechanical simplicity, reliability and ease of scalability. These favor them for space applications, where the image sensors need to be cooled to cryogenic temperature for enhanced vision [1]. The pulse tube is a thin-walled tube that acts as a displacer made of gas. The oscillating pressure created by the valveless compressor[2] makes the pulse tube act as a displacer. A gas volume that can replace a displacer is the best simplification in a mechanical standpoint.

A pulse tube cryocooler has an aftercooler to reject the heat of compression, regenerator, acceptor where the heat is removed at a lower temperature, and phase controller which controls the mass and pressure flow. An inertance pulse tube cryocooler has an inertance tube – reservoir combination as a phase controller. The phase controller assists the mass and pressure flow to have a phase difference at the acceptor. As for inertance tube- reservoir combination it mass and pressure lag at acceptor because of the

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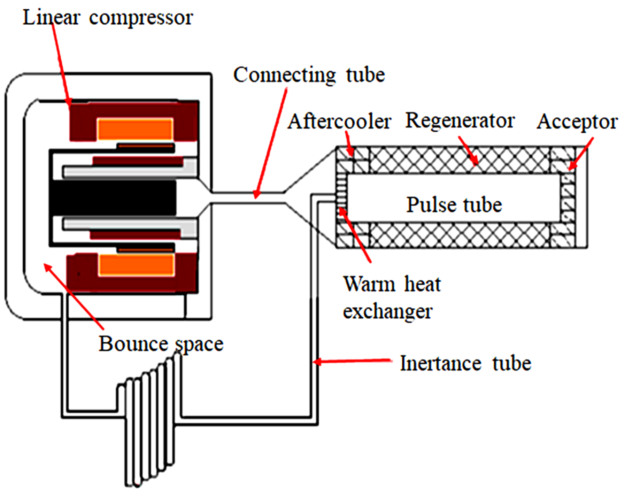

Figure 1. Pulse tube cryocooler with inertance tube- bounce space as phase controller.

phase shift. However, the inertance tube- reservoir has the disadvantage of bulky construction as the reservoir is a large tank. To reduce the size and a cryocooler using inertance tube- bounce space as phase controller could be used to make the cryocooler compact and with the best performance[3]. The objective of this paper is to optimize the parameters inertance tube, bounce space, regenerator and frequency to maximize the performance of pulse tube cryocooler. The simulation optimization of phase controller for pulse tube cryocooler is done using the Sage software.

PULSE TUBE CRYOCOOLER

Inertance Tube-Bounce Space as a Phase Controller

The phase controller for the inertance type pulse tube cryocooler consists of an inertance tube and reservoir. The inertance tube, as the name suggests, induces an inductance and resistance to the flow. The reservoir volume compensates for the pressure fluctuation and induces a capacitance. For the same reason, the reservoir will be large. There are modifications of the inertance pulse tube cryocoolers such as tandem type[4], active displacer[5], etc. The use of inertance tube- bounce space as phase controller uses the linear compressor's backspace to assist in phase shift. The phase difference between the compressor and bounce space flow is around 180º with lesser amplitude. If we can utilize phase difference, the inertance tube-bounce space combination can act as a compact phase controller.

A schematic of the pulse tube cryocooler, which uses inertance tube bounce space as phase controller, is shown in Figure 1. Here the inertance tube is connected to the bounce space i.e., the back space of the linear compressor. The bounce space will act as a variable reservoir with 180º phase shift with compression space, with the low mass flow and pressure flow. The cryocooler consists of a moving magnet linear compressor, aftercooler, regenerator, acceptor, pulse tube, warm heat exchanger, and inertance tube connected to the bounce space.

Sage Overview

Sage is a software for the design of wide variety of cryocoolers by David Gedeon of David Gedeon Associates in Athens, Ohio. Sage provides graphical interface to simulate and optimize the various cryocooler components such as heat exchangers, pulse tube, regenerator, compressor, and other components. Sage is a one-dimensional frequency domain modeler for modeling oscillating thermodynamic systems. Here the components are connected using mass flow, heat flow, force and displacement connections. Sage then solves the simultaneous equations of motion and heat transfer for the objects in the frequency domain at a given frequency. The results are in the form of dimensions, amplitude of pressure and mass, and heat interactions.

Table 1. Components and parameters

	Diameter (mm)	Length (mm)	Porosity(ε)
Compressor	19.8	12	
Connecting Duct	3.5	100	--
Aftercooler	26.38	5	0.65
Regenerator	26.38	74.2	0.786
Acceptor	26.38	2	0.65
Pulse tube	15	76.2	--
Warm heat exchanger	15	2	0.65
Inertance tube	3.5	3147	--
Bounce space	0-1000 cc		

Governing Equations

Sage's governing equations start with the Navier-Stokes equations in the integral form, then converted into one-dimensional differential equations in the conservative form. The equations then become:

Continuity:

$$\frac{\partial \rho A}{\partial t}+\frac{\partial \rho u A}{\partial x}=0 \tag{1}$$

Momentum:

$$\frac{\partial \rho u A}{\partial t}+\frac{\partial u \rho u A}{\partial x}+\frac{\partial P}{\partial x}A-FA=0 \tag{2}$$

Gas Energy:

$$\frac{\partial \rho u e A}{\partial t}+P\frac{\partial A}{\partial t}+\frac{\partial}{\partial x}(u\rho e A+uPA+q)-Q_w \tag{3}$$

The implicit solution variables are ρ, ρuA, and ρe. Terms F, Q_w, and q are terms with separate definitions.

Sage model

The modeling of the cryocooler is done with the Sage software[6]. The model has a linear compressor with bounce space, heat exchangers, regenerator, pulse tube, and phase controller. The linear compressor used is a moving magnet type. The heat exchangers, namely aftercooler, acceptor, and warm heat exchangers, are made of copper slits with a porosity of 0.65. The regenerator is made of stacked SS304 mesh with a wire diameter of 25 μm and size 400#. The pulse tube is a narrow tube made of SS304 with a wall thickness of less than 0.15 mm. At the end of pulse tube is the Warm heat exchanger made of copper, with slits having a porosity of 0.65. Important dimensions of the components are given in Table 1.

The cold head which includes the aftercooler, regenerator, acceptor, pulse tube, and warm heat exchanger is arranged inside coaxially. To include the effect of heat transfer between the pulse tube and regenerator component, which is significant in a coaxial arrangement, a 'heat transformer' is attached.

SAGE SIMULATIONS

The Sage simulations were done on the cryocooler for varying parameters such as frequency, regenerator length, inertance tube length, and the bounce space volume. The variation of the parameters was plotted against the cooling load and the Coefficient of Performance calculated at 80 K. The working fluid for the cryocooler is Helium. The charge pressure is 3.2 MPa.

The increase in frequency increases the mass flow rate but, the frequency affects the thermal penetration depth and the heat transfer rate. The performance of the cryocooler increases steeply with the increase in frequency before it deceases. Figure 2 gives the variation of cryocooler performance for the varying frequency of operation. The frequency was varied from 40 to 70 Hz. The maximum cooling load obtained was 2.76 W with an input power of 94.4 W. The maximum Coefficient of performance obtained was 2.92%.

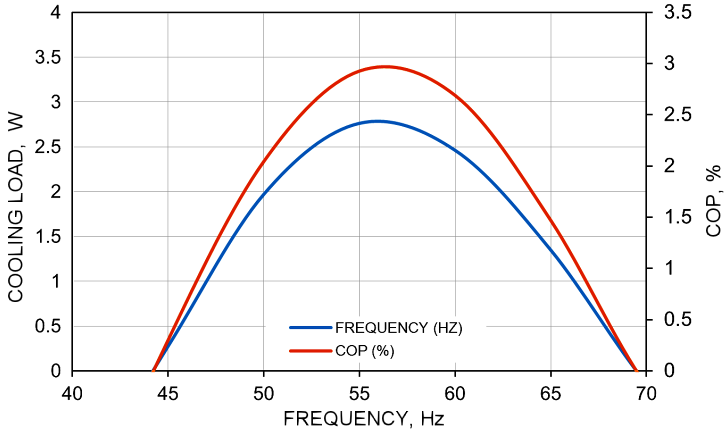

Figure 2. Cooling load and COP for varying Frequency

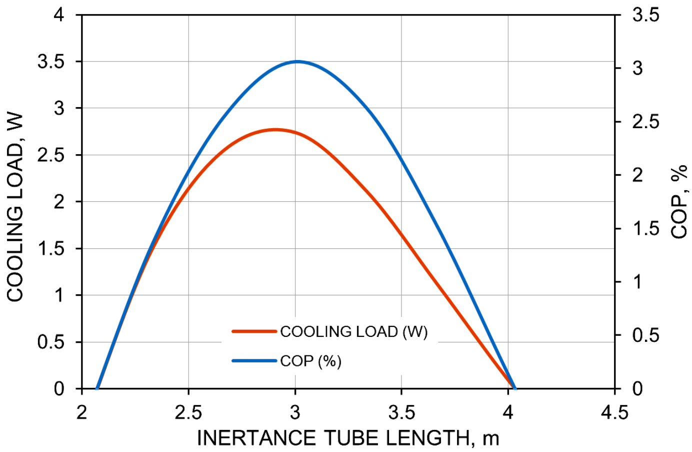

Figure 3. Cooling load and COP for varying inertance tube length

Figure 3 shows the cryocooler simulation for varying lengths of inertance tube from 2 m to 4.5 m with an inner diameter of 3.5 mm. The maximum cooling load obtained was at a length of 3m, for a maximum cooling load of 2.74 W at 80 K. The COP thus obtained was 3.5%, where the input power was 89.6 W. The increase in inertance tube length, increases the inductance effect for the cryocooler, increasing the performance. But the longer the length of the inertance tube, higher the pressure drop, decreasing the performance.

Design of regenerator, some compromise is to be considered as the length increases the overall capacity by increasing pressure drop, which decreases performance. Figure 4 shows the performance characteristics with varying the length of the regenerator from 30 mm to 100 mm. The cryocooler's maximum performance was obtained with a length of 53.3 mm with a cooling load of 3.72 W. The input power was 113.7 W making the COP of 3.33%. The performance of the cryocooler increases with the increase in regenerator length before dropping.

The purpose of the bounce space is to maintain a constant pressure flow by superimposing the pressure created by the compressor and the bounce space. Thus, ideally the super positioning of flow should lead to maximum performance with minimum volume. The favored condition will be to have a small bounce space volume as the pressure fluctuation developed in the bounce space could favor having a better phase shift. Figure 5 shows the simulation of cryocooler performance with varying bounce space volume from 50 to 1000 cc. When the bounce space volume was increased from 0 to 400 cc, there was a steady improvement in the performance of the cryocooler. Beyond which the increase in bounce space volume had signifi-

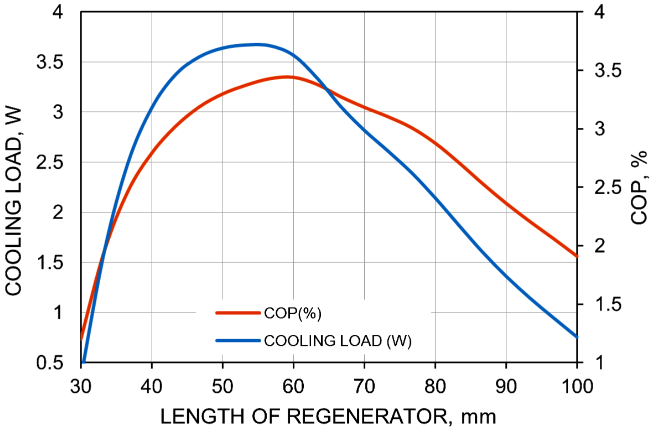

Figure 4. Cooling load and COP for varying length of regenerator

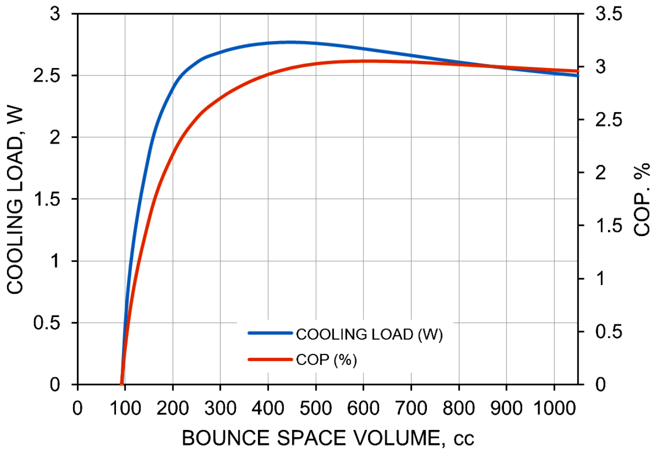

Figure 5. Cooling load and COP for varying bounce space volume.

cantly less effect on the cooling load and performance of cryocooler. A cooling load of 2.76 W was produced at 80 K with a bounce space volume of 400 cc. The COP of the cryocooler was 2.93% with an input power of 94.4 W. This figure gives a good indication of the minimum bounce space volume without affecting the performance.

OPTIMIZATION OF CRYOCOOLER

Input parameters

The required cooling power of the pulse tube cryocooler is above 2W. The input power depends on the compression ratio and mass flow. The cooling power is equal to the acoustic or PV power flow through the pulse tube minus the losses[7]. The design of pulse tube cryocooler should have minimum power optimizing the phase controller parameters. The basic dimensions of the cryocooler were given in Table 1.

Variables and constraints

The parameters optimized are length of inertance tube, length of regenerator, volume of bounce space, and frequency. As the arrangement is coaxial, a constraint is introduced as the length of pulse tube is equal to the sum of length of regenerator and acceptor. According to Sage software the limit of power input is to

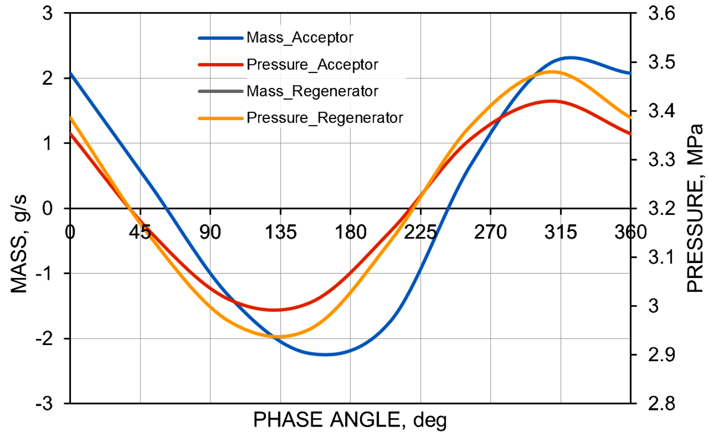

Figure 6. Variation of mass and pressure at regenerator and acceptor

be defined. The maximum power input to the compressor is 100 W. The dimensions of other components are done based on its suitability and prior experience.

Objective Function and Optimized Cryocooler

To suit the requirement and to optimize the inertance tube dimensions variable, constraints and objective functions are introduced to Sage V11. The variable parameters are the frequency, length of the inertance tube and the bounce space volume. The input power is in range of 0-100W is made as a constraint. The objective function is to maximize the cooling load. The optimized frequency was found to be 52.8 Hz. The optimized inertance tube and regenerator lengths were 3.86 m and 44.8 mm respectively. The bounce space volume was found to be 238 cc. The maximum cooling load was found to be 4.30 W with an input power of 100 W.

Characteristics of Optimized Cryocooler

Figure 6 shows the pressure flow and mass flow variation at the midpoint of acceptor and regenerator for the optimized cryocooler. The mass flow at the midpoint of the acceptor was found to be 2.366 g/s. The pressure flow amplitude was at the acceptor was found to be 2.194 $\times 10^5$ Pa and the phase shift between the two was found to be -24.5°. The figure plots the mass and pressure flow variation at the midpoint of the regenerator. The pressure amplitude was found to be 2.194 $\times 10^5$ Pa with a mass flow rate of 2.739 g/s. The phase shift between mass and pressure at the regenerator's midpoint was found to be 0°.

CONCLUSION

A cryocooler with inertance tube- bounce space as phase controller is optimized with the frequency, regenerator length, inertance tube length, and bounce space volume. The phase shift at the acceptor was found to be -24.5°. The maximum cooling load at 80 K was found to be 4.30 W. The COP was found to be 0.043, which is 16.12% compared to the ideal COP of pulse tube cryocooler.

ACKNOWLEDGMENT

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