Investigation of improving cool-down speed of Stirling type pulse tube cryocooler with ambient displacers

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Abstract. For a cryocooler, besides high efficiency at the working temperature, the cool-down speed is also important for some applications. Because of the difference in structure and operating mechanism, different cryocoolers have different characteristics for cool-down speed. This work introduces a Stirling type pulse tube cryocooler with ambient displacers which works in the liquid nitrogen temperature region. Strategies for improving the cool-down speed from room temperature to liquid nitrogen temperature have been investigated through simulation. The pulse tube cryocooler is designed to provide a nominal cooling power of 17.8 W at 77 K with 232.5 W of input electric power at 70 Hz. By fixing the maximum displacer movement in the simulation, the characteristics of how tuning the frequency around 70 Hz can change the cool-down speed without exceeding the allowable displacement of the piston and the current draw of the actual compressor are investigated. The strategy for tuning both the frequency and voltage turns out to be effective in the beginning stage of the cool-down process with an improvement of the cooling power by about 15%-20%. The gain becomes less obvious as the cold head temperature drops. In conclusion, tuning both the frequency and voltage during the cool-down process helps the cold-head to reach its final temperature faster but the average gain is not as big as expected.

1. Introduction
In most cases, the design of cryocoolers tends to focus on the performance at the working temperature region. For some special applications which need quick response, the cool-down speed is also important in addition to high efficiency at the working temperature. In some applications, the cryocoolers with a larger cooling capacity that exceed design requirements can be used to improve the cool-down speed. However, this usually results in increased costs and volume. Typically, when the temperature of the cold end decreases from room temperature to the target temperature, the impedance as seen by the compressor also changes. From the acoustic viewpoint, the impedance match between the cold-head and compressor is very important for optimizing the efficiency of the compressor as well as maximizing the power capacity of the compressor [1]. As a result, the cryocooler may not operate under an optimum condition during the cool-down process without careful tuning of the operating parameters. Radebaugh et al. [2] connected two reservoirs in series through valves in a pulse tube cryocooler that used an inerter tube
and reservoir combination. The smaller reservoir is used to generate more acoustic power at the cold end when the cryocooler works at near room temperature. Zhou et al. [3] introduced a phase shifting mechanism using a tunable inertance tube by adjusting the diameter and length of inertance tube while the cryocooler is operating. But the effect of the adjustable inertance tube on the cool-down speed of cryocooler was not discussed or studied.

This paper numerically studies a Stirling type pulse tube cryocooler with ambient displacers TC4189 that works in the liquid nitrogen temperature region [4]. To improve the cool-down speed from ambient temperature to the working temperature, both the frequency and voltage are tuned in order to generate a bigger cooling power as the temperature of the cold end drops. Meanwhile, the displacement limit of piston/displacer and the current limit of the compressor are taken into account. The following gives an evaluation of the effectiveness of the strategy.

2. Configuration of Cryocooler

![Figure 1. The structure of Stirling type pulse tube cryocooler.](image)

The configuration is shown in Figure 1. It adopts an integral single-stage configuration. The cold head comprises an ambient heat exchanger, regenerator, cold heat exchanger, pulse tube, second ambient heat exchanger, expansion volume and displacer. The compressor is of the moving-magnet type. Both compressor pistons and displacers use a dual-opposed configuration to reduce vibration. The compressor pistons are supported by gas bearings while the displacers are supported by flexure bearings. Gray arrows in Figure 1 illustrate the simulated work flows in the system. The parameters of the main components are listed in table 1.

| Item                  | Values   |
|-----------------------|----------|
| **Input Parameters**  |          |
| Frequency, Hz         | 70       |
| Operating pressure, MPa | 4.0     |
| Working fluid         | Helium   |

**Table 1. Operating parameters and dimensions of main component.**
3. Simulation and Analysis

Sage is used to simulate the system in this work [5]. Two important concepts are defined here. The impedance of the cold head as seen by the compressor piston is defined as

$$Z = \frac{\hat{P}_1}{\hat{U}_1}$$  \hspace{1cm} (1)

where $\hat{P}_1$ and $\hat{U}_1$ are the complex amplitude of the oscillating pressure inside the compression space and the oscillating volumetric flow rate equal to the speed of piston times the area of the piston. $^\wedge$ is the complex form of the dynamic variables, which contains the amplitude and phase of the dynamic variable.

$$E_2 = \frac{1}{2} \text{Re}[\hat{P}_1 \hat{U}_1^*]$$  \hspace{1cm} (2)

$E_2$ is the acoustic power, $\hat{P}_1$ and $\hat{U}_1$ are pressure and volume flow rate and $^*$ represents the conjugate.

Table 2 is the main simulated design result of the cryocooler at liquid nitrogen temperature. The cryocooler can produce a cooling power of 17.8 W at 77 K with 232.5 W of input electric power. The cryocooler is designed to have a good impedance match with the compressor when it operates in the working temperature region with a 70 Hz working frequency, which results in a compressor efficiency of 77.2% (output acoustic power divided by electric power input).

### Table 2. Performance of cryocooler at working temperature region.

| Parameters                     | values     |
|-------------------------------|------------|
| Compressor                    |            |
| Input compressor electricity, W | 232.5      |
| Compressor efficiency         | 77.2%      |

| Diameter of piston, mm         | 24         |
| Displacement of piston, mm     | 4          |
| Maximum Current, A             | 13         |
| Displacer                      |            |
| Displacement of displacer, mm  | 1.46       |
| Diameter of displacer, mm      | 22         |
| Displacer moving mass, kg      | 0.0288     |
| Displacer spring constant, kN/m| 34.2       |
| Regenerator                    |            |
| Outer diameter, mm             | 22.5       |
| Inner diameter, mm             | 9.0        |
| Length, mm                     | 40         |
| Wire diameter, mm              | 1.35E-02   |
| Porosity                       | 78%        |
| material                       | stainless steel random fiber matrix |
| Cold end heat exchanger        |            |
| Form                           | Radial fins heat exchanger |
| Fin thickness, mm              | 1.08       |
| Channel width, mm              | 0.15       |
| Channel height, mm             | 3.5        |
| Inner diameter, mm             | 9          |
| Outer diameter, mm             | 22.5       |
| Channel number                 | 40         |
| Material                       | copper     |
| Mass, kg                       | 0.2        |
To decrease the cool-down time, the net refrigeration power should be increased beyond that normally available over the whole temperature range. One approach is to increase the input power by increasing the input voltage without changing the frequency. However, both the displacement limit and current limit, as listed in Table 1, should be observed. Another option is to tune both the frequency and voltage simultaneously at various temperature regions. Of the two moving objects, the compressor piston and the warm displacer, the displacer is most likely to reach its displacement limit in our study (which will be seen in Figure 4), and is therefore the main parameter of concern in the following discussion.

In the following sections, we first investigate the system characteristics with a fixed design frequency but with constant voltage and variable voltage. The subsequent sub-section explores the system characteristics when tuning both the frequency and voltage in different temperature regions. In the third sub-section, the cool-down time is calculated while varying the modes.

3.1 Effects of tuning voltage at the nominal frequency

In the first set of calculations, the cryocooler operates at the fixed nominal frequency during the whole cool-down process. Figure 2 shows the variation of input voltage, displacer displacement, current of the compressor and cooling power with the decrease of cold head temperature with two different modes, viz, constant voltage and constant displacer displacement. It can be inferred from Figure 2(a) that if a constant voltage is used to drive the cooler, the voltage value should be the minimum at near 170 K to avoid exceeding the displacement limit. The difference of cooling power and current between two different modes is shown in Figure 2(b). By varying the input voltage to keep a constant maximum displacer displacement, the cooling power at temperatures on both sides of 170 K can be increased compared with the constant voltage mode, however the effect is very minimal.

As will see later in Figure 3, the efficiency of the compressor at 70 Hz decreases with an increase of temperature at the cold head due to the mismatch of impedance between the compressor and cryocooler. When it operates near room temperature, the impedance of a cold head will deviate significantly from the designed condition.

| Pressure ratio | 1.3 |
|----------------|-----|
| Ambient heat exchanger temperature, K | 308 |
| Cold heat exchanger cooling power | 17.8W@77K |
| Relative Carnot efficiency based on acoustic power | 29.7% |

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![Figure 2](image1.png)

(a) Input voltage and displacement of displacer.

![Figure 2](image2.png)

(b) Cooling power and current.

Figure 2. The variation of characteristics of two cool-down processes under design frequency.

3.2. Effects of tuning both frequency and voltage.

Figure 3 shows the variation of impedance and compressor efficiency at different frequencies with the increase of temperature at the cold head. From the simulation, it is known that the displacement of the
displacer is the main reason for limiting the input power. In order to increase the cool-down speed, the strategy of changing the operating frequency in different temperature regions in order to achieve the maximum cooling power within the displacement limits of the piston and displacer is investigated.

Figure 4 shows the change of current and displacement of the piston with an increase in temperature at the cold head under different operating frequencies, all the while staying under the maximum displacement limit of the displacer. As the operating frequency is reduced, and especially near room temperature, the input current increases noticeably and the displacement of the piston increases accordingly. This is related not only to the use of a larger input voltage, but also to the deviation from the resonant condition. In the figure, as the frequency decreases, the range of the operating temperature increases because the current or displacement of the piston exceeds its maximum displacement limit before the displacer exceeds its limit. In other words, if the lower frequencies are used near the room temperature, the displacement of piston will exceed the limit when we fix the displacement of displacer at 1.46 mm by increasing the input voltage.

Figure 5 shows the change of electrical power and cooling power as the temperature of the cold head increases under different operating frequencies. At the same temperature of the cold head, the electrical power and cooling power increase as the operating frequency decreases. In other words, more power can be input and the compressor can provide more acoustic power at lower operating frequencies. The increase of input power is especially obvious in the room temperature region. When the displacement of displacer is fixed, the cryocooler runs at a lower frequency at the beginning of the cool-down process and a higher input voltage can be adopted compared with the condition when the cryocooler is operating at 70 Hz. The cooling power can be increased by about 15-20\% at the beginning of the cool-down process. But when the temperature of the cold head drops below 200 K, the increase of cooling power is very limited. Figure 5 also shows the change of the relative Carnot efficiency based on acoustic power and electrical power as a function of the cold head temperature under the maximum displacement of displacer. The frequency has little effect on the relative Carnot efficiency based on acoustic power.
3.3 A rough estimation and comparison of cool-down time.

According to the following equations, the net cooling power of the cryocooler discussed here directly influences the cooling time of cryocooler.

\[ \dot{Q}_{\text{net}} = -mc_p \frac{dT}{dt} \]  

where \( m \) is the mass of the cold end heat exchanger (0.2 kg), and \( c_p \) is the temperature-dependent specific heat of the cold end heat exchanger whose material is oxygen-free copper. \( T \) and \( t \) are the temperature of the cold end heat exchanger and time. From the results presented in the previous sections, the cooling power can be expressed as functions of the cold end temperature. The expression for the cooling time as a function of the final and initial temperature of the cold end is obtained by rearranging and integrating the above equation.

\[ \Delta t = m^* \int_{T_1}^{T_2} \frac{c_p}{\dot{Q}_{\text{net}}} dT \]  

\( \Delta t \) is the cooling time from the initial temperature \( T_1 \) to the final temperature \( T_2 \) of the cold end. The initial temperature is 300K, and the final temperature is 77K. Equation. 5 shows the variation of the specific heat with temperature and the corresponding coefficients of the equation are listed in Table 3. The data of the specific heat of copper is from the data base given by NIST [5]. The time it takes to cool down from room temperature to the various cold end temperatures can be calculated based on the above equation. The comparison is concerned with the effectiveness of the cool-down strategy compared with other two modes, therefore the specific heat of the regenerative material is not considered in the calculation of cooling time.

\[ c_p = 10^{(a+b(\log_{10} T)+c(\log_{10} T)^2+d(\log_{10} T)^3+e(\log_{10} T)^4+f(\log_{10} T)^5+g(\log_{10} T)^6+h(\log_{10} T)^7)} \]  

| coefficients | values   |
|--------------|----------|
| a            | -1.91844 |
| b            | -0.15973 |
| c            | 8.61013  |
| d            | -18.996  |
| e            | 21.9661  |
| f            | -12.7328 |
Figure 6 shows the variation of the cooling power and input voltage as a function of the cold head temperature under the three different operation conditions. In the first case the input voltage is held fix along with a constant frequency of 70 Hz. In the second case the displacement of displacer is held fixed along with a constant frequency of 70 Hz. In the third case the frequency and voltage are tuned simultaneously during the cool-down process while maintaining the displacer at its limiting value (1.46mm). The frequency we use in the various temperature regions in the third case ensures that the cooling power is maximum by pushing the displacement of the displacer to its limit.

![Figure 6](image)

**Figure 6.** the variation of cooling power and input voltage of cryocooler with the increase of temperature of cold head.

Figure 7 shows the calculated results of the cool-down time according to Eq.(4). The results indicate that the first process requires the largest amount of time (about 344 seconds) to reach the working temperature. The second cooling process operating at 70Hz takes about 334 seconds to reach 77 K, and the third cooling process operating at various frequencies and voltage takes about 313 seconds to cool down to 77 K. In general, the strategy for improving the cool-down speed from room temperature to liquid nitrogen temperature has achieved a certain effect.
4. Conclusion
This report has investigated various methods to improve the cool-down speed of Tc4189, which is a Stirling type pulse tube cryocooler with ambient displacers. Because the displacer is more likely to reach its displacement limit than the compressor piston in this configuration, we have focused on strategies that maintain the displacer below its displacement limit while tuning the input voltage or the input voltage together with the operating frequency in different cool-down temperature regions. Compared with the cool-down process in a constant voltage mode, the strategy of tuning both the voltage and frequency turns out to be more effective in the beginning stage of the cool-down process producing an improvement of cooling power by about 15%-20%. The effectiveness decreases gradually as the cold head temperature drops. For the cool down from 300 to 77 K, the strategy can shorten the time from around 344 seconds to about 313 seconds. In conclusion, tuning both the voltage and frequency during the cool-down process helps the cold-head to reach its final temperature faster but the average gain is not as large as expected.

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