GM / Pulse Tube Cryocoolers

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Vibration Analysis of Cryocoolers

Characteristics of 4 K pulse tube cryocoolers in applications

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Vibration analysis of cryocoolers ☆

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Abstract

The vibrations of Gifford-McMahon (GM) and pulse-tube (PT) cryocoolers were measured and analyzed. The vibrations of the cold-stage and cold-head were measured separately to investigate their vibration mechanisms. The measurements were performed while maintaining the thermal conditions of the cryocoolers at a steady state. We found that the vibration of the cold-head for the 4 K PT cryocooler was two orders of magnitude smaller than that of the 4 K GM cryocooler. On the other hand, the vibration of the cold-stages for both cryocoolers was of the same order of magnitude. From a spectral analysis of the vibrations and a simulation, we concluded that the vibration of the cold-stage is caused by an elastic deformation of the pulse tubes (or cylinders) due to the pressure oscillation of the working gas.

Keywords: Cryocooler; Vibration; Pulse-tube; Gifford-McMahon

1. Introduction

Practical use of a small vibration cryocooler is expected by the technical development of a pulse-tube (PT) cryocooler. Devices for which such a small vibration cryocooler is needed are a superconducting-filter in information technology, a magnetic-resonance imaging in medicine, an electron microscope in science, an infrared detector, a cryogenic interferometric gravitational wave detector [1] and so on. For an electron microscope, there is a report that the resolution of the microscope was improved by exchanging a Gifford-McMahon (GM) cryocooler to a PT [2].

However, there are only a few reports about vibration evaluations of these cryocoolers [3,4]. Therefore, we developed a vibration measurement method for the cryocoolers, and analyzed their vibrations for three cryocoolers. From the measured results, we found the difference of the vibrations between the GM and PT cryocoolers, and their vibration-mechanism.

2. Measurement apparatus

The purposes of our experiment were to show the vibration-amplitude for PT and GM cryocoolers, and to understand their vibration mechanism. To achieve the above, we developed a vibration measurement method for cryocoolers.

Fig. 1 shows the measurement apparatus. In this experiment, the cold-head of the cryocooler was mounted on a vacuum chamber, and the cold-stage was set below.

A feature of this apparatus is to be able to measure the vibrations of cryocoolers at a thermally steady state. In our preparatory measurement, we had already confirmed that an exact vibration-measurement of cryocoolers has to be performed at steady state, since their vibration amplitudes were different between the beginning of the cool-down and the steady state [5]. In this measurement, the achieved temperatures of the cryocoolers were higher than the nominal temperatures, since we used no radiation shield for simplicity.

Besides the vibration of the cold-stage, vibration of the overall cold-head due to the motions of the flexible tubes and the displacer can exist. This type of vibration affects cooled objects by vibrating the overall cryogenic system and vibrational conduction through the surface of the cryostat. Since the cause of vibrations for the

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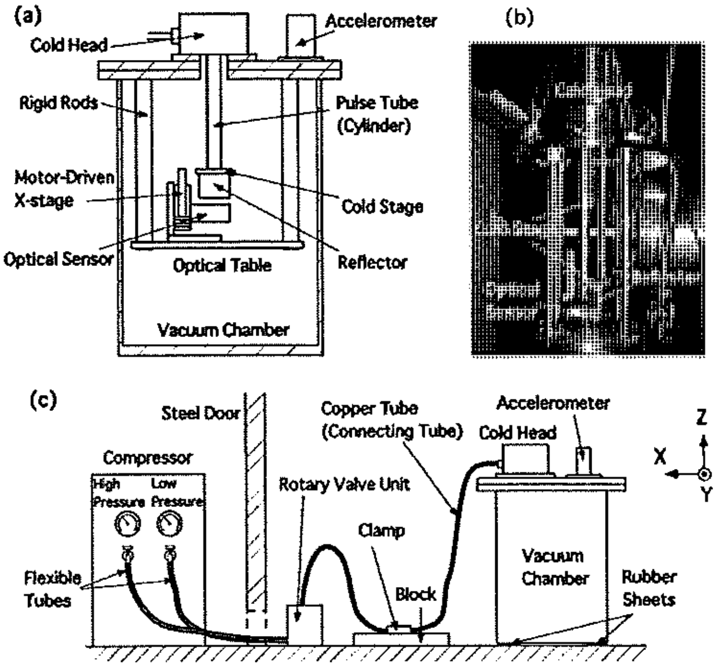

Fig. 1. Vibration-measurement apparatus for cryocoolers. (a) Setup of the sensors, (b) photo of the cryocooler setup and sensors, and (c) overall apparatus setup. The optical sensor monitored the motion of the cold-stage and an accelerometer measured the acceleration of the cold-head separately. The optical sensor was calibrated by moving a motor-driven X-stage. A copper tube (connecting tube) between the cold-head and rotary valve unit was clamped onto a 24 kg block to reduce vibrations from the rotary valve unit and compressor. For the GM cryocooler, flexible tubes that connected the cold-head and compressor directly were clamped to the block. The compressor was located in the next room. The direction parallel to the flexible tubes or connecting tube was defined as the "X" axis, the direction perpendicular to "X" in a horizontal plane was defined as "Y", and the direction vertical to "X" was defined as "Z". Only for the Sumitomo 4 K PT cryocooler, "X" was defined in a direction parallel to a row with a pulse tube and regenerator at the second cold-stage, and "Y" was defined as the direction perpendicular to "X".

cold-stage and the cold-head is completely different, these vibrations have to be measured separately to understand their vibration mechanism. Therefore, we devised a measurement apparatus to be able to measure them separately.

One way to measure the vibration of the cold-stage alone is to measure the relative displacement of the cold-stage while referring to the cold-head motion. To achieve the above, we set a rigid table below the top flange of the vacuum chamber that the cold-head was mounted on. This table consisted of four stainless-steel rods of 38 mm in diameter and 500 mm in length, and an aluminum plate of 300 mm in diameter and 20 mm in thickness. Since the resonant frequencies of the table were over 200 Hz for all measurements, we regarded that the table moved with the cold-head below the resonant frequencies. We set an optical displacement sensor (reflective type) on the table, and measured the relative displacement of the cold-stage which referring to the table. Fig. 2 shows a schematic diagram of the optical sensor. The measurement principle of this sensor is that the displacement between the sensor and the reflector is converted from the change of the light power, which is emitted from the LED, reflected by the reflector and detected by photo-detectors. A high-power *GaAlAs* diode (890 nm in wavelength) was used as the LED, and two *InGaAs* PIN photo-diodes were used as a photo-detector. These diodes can work even at liquid-helium temperature. [1] The reason why two photo-detectors were used was to reduce the error due to the tilt between the sensor and the reflector. The sensor output was low-

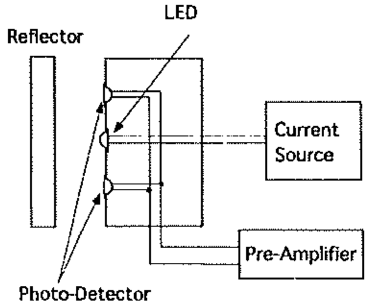

Fig. 2. Schematic diagram of the optical displacement sensor (reflective type).

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[1] Although we devised to be able to compensate the sensitivity change of the sensor due to its cooling down by attaching a thermometer on it, the sensor was not cooled at all, since we did not use any radiation shields.

Table 1
Specifications of measured cryocoolers manufactured by Sumitomo Heavy Industries Ltd. and Aisin Seiki Co. Ltd.

Manufacturer	Sumitomo	Sumitomo	Aisin
Type	4 K GM	4 K PT	40 K PT
Cold-stages	2 Stage	2 Stage, U-type	1 Stage, co-axial
Compressor	7 kW, air cooling	7 kW, air cooling	0.8 kW, air cooling
Temperature	15–16 K	28–35 K	74–79 K
Operating frequency (Hz)	1	1	3.8
Filling pressure (MPa)	1.7	1.7	1.2

"Temperature" in the column means achieved temperature in this experiment.

pass filtered at 1.6 kHz in the pre-amplifier of the sensor. A polished aluminum block of 750 g was used as a reflector and attached under the cold-stage. In order to measure the exact displacement even when the cold-stage was at cryogenic temperature, we set the optical sensor on a motor-driven X-stage and calibrated it just before each measurement.

For a vibration measurement of the cold-head, we used commercial accelerometers. A laser accelerometer (RION Co., LA-50) was used for the PT cryocoolers and a piezo-electric accelerometer (TEAC Co., Model 710) was used for the GM cryocooler to suit to their vibration levels. Since these accelerometers could not work in a vacuum, we set them on the vacuum chamber. Therefore, we could not eliminate the sound effect conducted through the air.

A compressor, which could generate large vibrations, was located in the next room, and separated by a steel door to reduce the sound effect. To reduce the effects of the motion of the flexible tubes and direct vibration conduction from the compressor, the tubes were clamped on a 24 kg block. For the PT cryocoolers, a rotary valve unit and a cold-head were connected by a rigid copper tube, and the tube was clamped on the block. Measurements were carried out at night to reduce vibrational background noise coming from the surroundings, and all vacuum pumps were stopped during the measurements.

3. Vibration measurement and analysis

3.1. Guideline of measurement

Table 1 gives the specifications of the measured cryocoolers [6,7]. [2] For each cryocooler, we acquired vibrational spectra and time-series data. The measurements were performed for the vertical and two horizontal directions. In this experiment, the direction parallel to the flexible tubes or the connecting tube was defined as the "X" axis, the direction perpendicular to "X" in the horizontal plane was defined as "Y", and the direction vertical to "X" was defined as "Z" (see Fig. 1). For the Sumitomo 4 K PT cryocooler, "X" was defined in a direction parallel to a row with a pulse-tube and regenerator at the second cold-stage, "Y" was defined as the direction perpendicular to "X" and "Z" was defined as the vertical direction, since the arrangement of the pulse-tubes and regenerators was complex.

In this paper, we described the vibrational spectra by the following displacement-density [8]:

$$\tilde{x}(\omega) = \left[\lim_{T\to\infty}\frac{1}{T}\left|\int_{-T/2}^{T/2} x(t)\mathrm{e}^{-\mathrm{i}\omega t}\,\mathrm{d}t\right|^2\right]^{1/2} \quad (\mathrm{m/Hz^{1/2}}), \quad (1)$$

where $x(t)$ gives time-series data of the vibrational displacement, T is the time-length during the measurement and ω is the angular frequency.

The measured frequency range was from 0.1 to 800 Hz. To achieve a sufficient frequency resolution, we measured the spectra at a width of 0.0125 Hz between 0.1and 10 Hz, at a width of 0.125 Hz between 10 and 100 Hz and at a width of 1.25 Hz between 100 and 800 Hz. The vibrational spectra are described in root-mean-square (RMS) in this paper. A flowchart of the data acquisition is shown in Fig. 3.

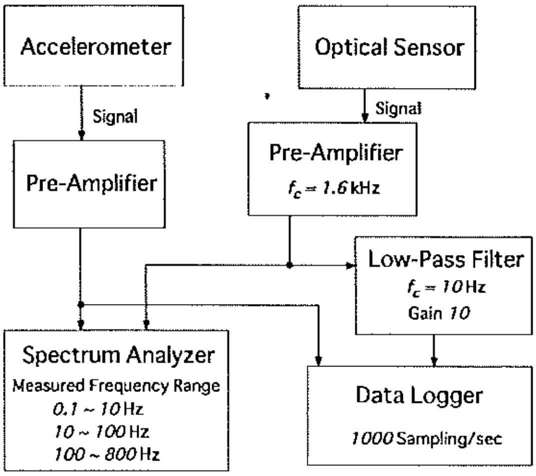

Fig. 3. Flowchart of the data-acquisition.

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[2] Although we also measured a 10 K GM cryocooler (2.4 kW, water cooling) manufactured by Sumitomo Heavy Industries Ltd., the data were omitted in this paper, since the data were almost same as that of the 4 K GM for vibrations of the cold-head and the cold-stage.

Table 2
List of the resonant frequencies for each part of the 4 K cryocoolers

Direction	*X*	*Y*	*Z*
Sumitomo 4 K GM			
Ground	$\underline{20}$, 75	–	$\underline{50}$, $\underline{90}$
Rubber sheet	24, 76, 99, 115, 130	$\underline{20}$, 46, 72, 110, 126, 153	$\underline{90}$, 110, 132
Flexible or connecting tubes	20, 40, 75, $\underline{106}$, 199, 262	13, 17, $\underline{20}$, 33, 71, 73, 152, 203, 265	18, $\underline{20}$, 78, 117, 185, 235
Top flange	14, 18, 22, 75, 115	46, 72, 109	89
Top of cold-head	14, 18, 22, 75	–	$\underline{20}$, $\underline{90}$
Optical table	115	–	223
Optical sensor	290	–	–
Cold-stage	115	–	116
Sumitomo 4 K PT			
Ground	75	70	80
Rubber sheet	–	–	–
Flexible or connecting tubes	25, 38, 60	25, 37, 60	110, 150
Top flange	75	11, 17	$\underline{12}$, 80
Top of cold-head	–	–	–
Optical table	210	–	210
Optical sensor	240	–	120, 260
Cold-stage	110	90	88, 115

The left column in the list gives the tapped parts. The listed values are shown in Hz. Relatively large resonances below 300 Hz are listed in this table. The underlined values show the central value of a broad peak, and hyphens are entered where data was not measured. The resonant frequencies of the optical table, optical sensor and cold-stage were measured using an optical sensor, and others were measured by accelerometers.

3.2. Resonant-frequency measurement for each part of the cryocoolers

Firstly, we must investigate the resonant frequencies for each part of the cryocoolers by tapping on the parts. By comparing the vibrational spectra of the cryocoolers with a list of resonant frequencies, we can identify the vibrational parts in the cryocooler and their vibrational amplitudes. Table 2 lists the tapped parts and the measured resonant frequencies for the 4 K cryocoolers. In this table, we listed relatively large resonances mainly observed below 300 Hz. Although several resonances depended on the experimental setup, and we could not note all data, we listed the noted resonant frequencies as they are in this table. The directions of the measurements were followed by the definition given in Fig. 1.

Since the structure of cryocoolers is complex, it was difficult to identify the resonant frequencies of the tapped part by eliminating other resonances. Especially, we observed many resonances of the flexible tubes and the connecting tube from low frequencies. The resonant frequencies of the cold-stages (pulse-tube and cylinder) were observed at around 100 Hz for all of the cryocoolers. For the Sumitomo 4 K PT cryocooler with a U shape and two stages, two resonances were observed.

3.3. Result

Fig. 4 shows the vertical vibration spectra for the measured cryocoolers. The light-blue lines in the graphs are sensor-noise (background-noise) when the cryocoolers were stopped, and the red lines are vibrational data when the cryocoolers were at a steady state. Moreover, Fig. 5 shows vertical vibration data in time-series for the 4 K cryocoolers. In Fig. 4, the vibrational spectra of the cold-head measured by accelerometers are shown by the displacement-density ($\mathrm{m/Hz^{1/2}}$) converted from the acceleration-density ($\mathrm{m/s^2/Hz^{1/2}}$), and in Fig. 5, the graphs for the cold-head are described by acceleration ($\mathrm{m/s^2}$).

Firstly, we describe the vibrations of the cold-stages. A special feature in the vibrational spectra of the cold-stages is sharp peaks with a driving frequency (1 Hz for Sumitomo and 3.8 Hz for Aisin) and its higher harmonics. The peaks with a driving frequency were especially large, and their displacements were almost the same as the total displacements for the overall measured frequency range. We summarize the vertical displacements of the cold-stages in Table 3. [3] In the case of two-stage cryocoolers, the displacement (peak-to-peak value) of the cold-stage for the 4 K GM cryocooler was 24 $\mu\mathrm{m_{pp}}$, and that for the 4 K PT cryocooler was 14 $\mu\mathrm{m_{pp}}$. That is, the vibration of the cold-stages for both cryocoolers were of the same level. On the other hand, that for the Aisin 40 K cryocooler with one-

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[3] The displacements of the cold-stages were calculated by integrating their spectra. Although there are small differences of the values between the spectral data and the time-series data, since they were not measured at the same time, the differences were a level of measurement error. For the Aisin 40 K cryocooler, we calculated the total displacement by using the spectral data below 40 Hz, since the line-noise (50 Hz) was not negligible. For the accelerations of the cold-heads, we listed the largest values during the measurements.

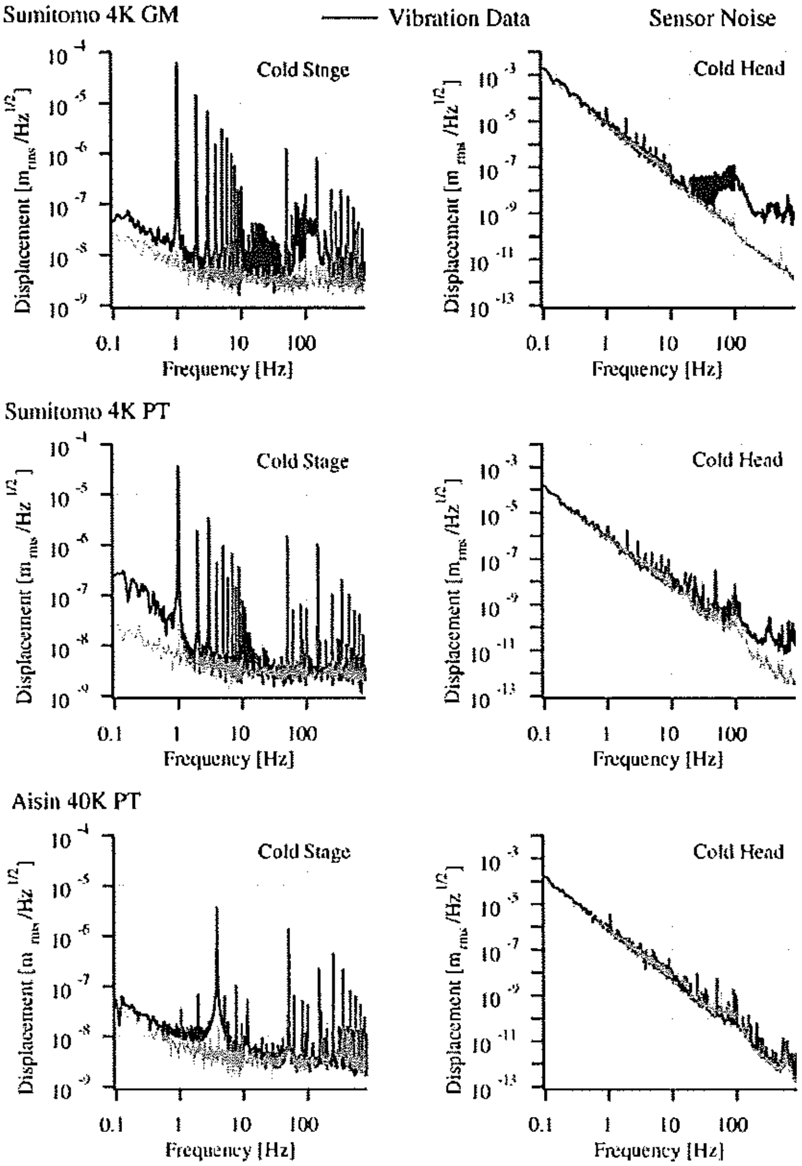

Fig. 4. Vertical vibration spectra for the cryocoolers. The blue lines show the sensor-noise-spectra and the red lines show the vibration spectra of the cryocoolers. The vibration amplitudes are shown in displacement spectral densities in RMS ($m_{rms}/Hz^{1/2}$).

stage was 1.4 μm_{pp} and one order of magnitude smaller than that of the two-stage cryocoolers. Study of the cause of the cold-stage vibration was described in Section 4.

The peaks at 50 Hz and its higher harmonics were the line-noise; they also appear in the noise-spectra. The time-series data in Fig. 5 were low-pass filtered at 10 Hz to eliminate the line-noise. In several spectra, we found an excess displacement at low-frequency range below 1 Hz. Especially, this excess displacement was large for the 4 K PT cryocooler. However, we could not understand the cause.

Next, we describe the vibration of the vacuum chamber on which the cold-head was mounted. As mentioned in Section 2, the cold-head vibration of the GM cryocooler was measured by a piezo-electric accelerometer, and those of the PT cryocoolers were measured by a laser accelerometer corresponding to their vibration-level. Therefore, the noise-levels of the accelerometers are different among the spectra.

A remarkable difference of the vibrations between the GM and PT cryocoolers was for the acceleration of the cold-head. From the time-series data in Fig. 5, the maximum acceleration of the cold-head for the 4 K GM cryocooler was about ±10 m/s^2; on the other hand, that for the 4 K PT cryocooler was about ±0.1 m/s^2. That is, the cold-head vibration of the GM cryocooler was two orders of magnitude larger than

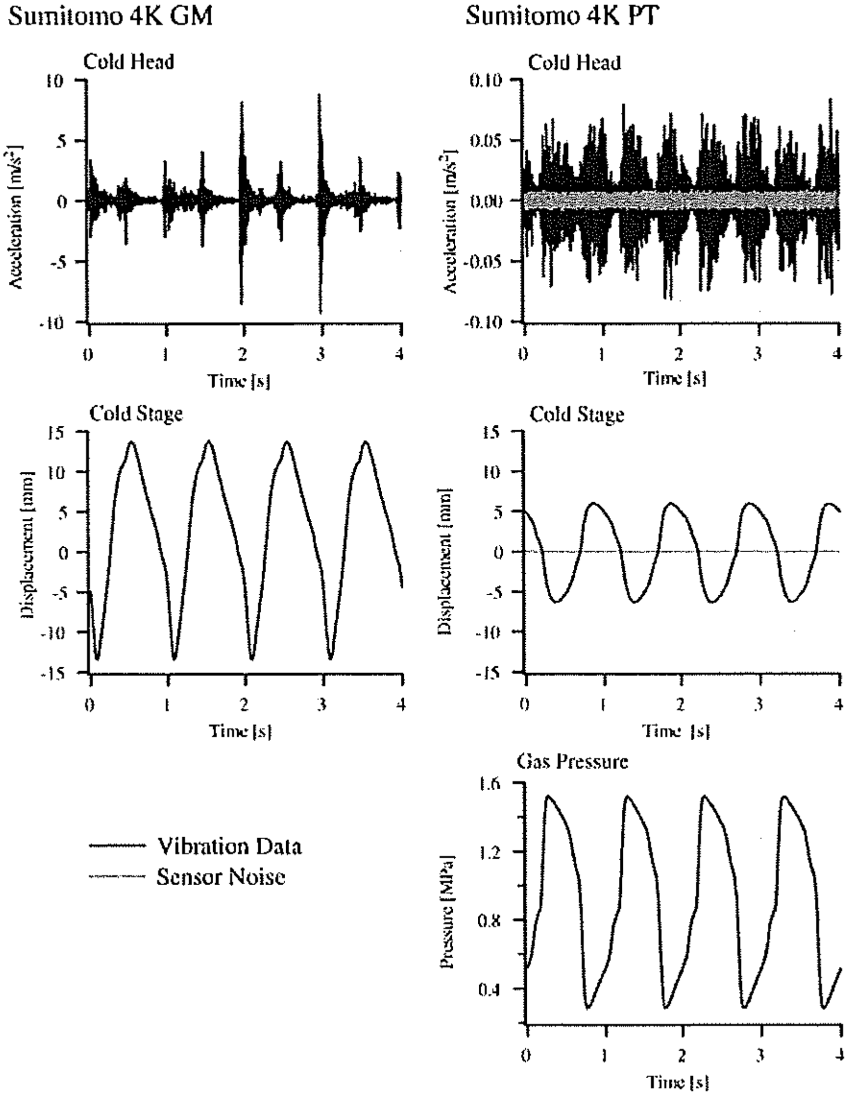

Fig. 5. Vertical vibration amplitudes of the Sumitomo 4 K GM and Sumitomo 4 K PT cryocoolers. The vibration of the cold-stage is shown in displacement (μm) and that of the cold-head is shown in acceleration (m/s^2). In the vibration data of the cold-stage and cold-head for the 4 K PT cryocooler, the sensor-noises when the cryocooler was stopped are shown as blue lines. The scale of the graph of the cold-head vibration for the PT cryocooler is two orders of magnitude smaller than that for the GM cryocooler. The pressure oscillation of the working gas for the PT cryocooler was measured at an outlet of the rotary valve unit.

Table 3
List of the measured vertical vibration amplitudes for cryocoolers

	Sumitomo 4 K GM	Sumitomo 4 K PT	Aisin 40 K PT
Maximum acceleration of the cold-head (m/s^2)	10	0.1	Sensor-noise-level
Displacement of the cold-stage at vibration peak (μm$_{pp}$)	24 (1 Hz)	14 (1 Hz)	1.4 (3.8 Hz)
Total displacement of the cold-stage (μm$_{pp}$)	26	15	1.4

The maximum accelerations of the cold-head were chosen from all of the measured time-series data. The vibration amplitudes (peak-to-peak) of the cold-stages were calculated from the spectral data by integrating them.

that of the PT. The measured maximum accelerations of the cold-heads are also listed in Table 3. This large acceleration for the GM cryocooler was observed when the displacer struck the cold-head. Then, the acceleration was not constant, but sometime large with a strange sound. A cause of this large acceleration could be because the displacer rubbed against the cylinder.

From the spectrum in Fig. 4, we found that this cold-head vibration mainly had frequency components above 10 Hz. From the list of resonant frequencies for the GM cryocooler, the wide peak at around 100 Hz in the spectrum can come from the resonances of the top flange of the vacuum chamber and the rubber sheets. Also, many small peaks between 10 Hz and 100 Hz can come from motions of the flexible tubes. Above 100 Hz, we estimated that the vibrations came from the superposition of many structural resonances and the sound effect through the air. On the other hand for the 4 K PT cryocooler, although we observed vibrations above 10 Hz, such as the GM, its amplitude was much smaller than that of the GM. This excess vibration can also come from the resonances of the rubber sheets, the connecting tube, the sound effect and so on. In the case of the Aisin 40 K PT cryocooler, we did not observe any prominent vibrations, since it has a small cold-head and a compressor. Below 10 Hz, the cold-head vibrations for all of the cryocoolers were sensor-noise-level.

In short, we found that the motion of the displacer of the GM cryocooler did not cause cold-stage vibration, such as in the usual consideration, but caused overall vibration of the cold-head. This is a reason why the vibration of a PT cryocooler is smaller than that of a GM.

However, the 4 K PT cryocooler also had larger vibrations of the cold-head than the sensor-noise-level. This type of vibration depends on the setup. That is, the vibration-level of the cold-head depends on how to set the cold-head and the connecting tube to the cryogenic system. This is a key point in designing a small-vibration cryogenic system by using cryocoolers.

Finally, we show the horizontal (X direction) vibration-spectra of the 4 K cryocoolers in Fig. 6. The peaks at 1 Hz and its higher harmonics in the graphs of the cold-stage vibrations appeared as vertical-horizontal coupling. The peaks around 100 Hz in the cold-stage vibrations came from the resonances of the pulse-tube or the cylinder. These vibrations also exist in the vertical spectra in Fig. 4 as horizontal-vertical coupling. For the cold-head, the horizontal vibration of the 4 K GM cryocooler was smaller than that of the vertical direction. In the case of the 4 K PT cryocooler, the vibrations

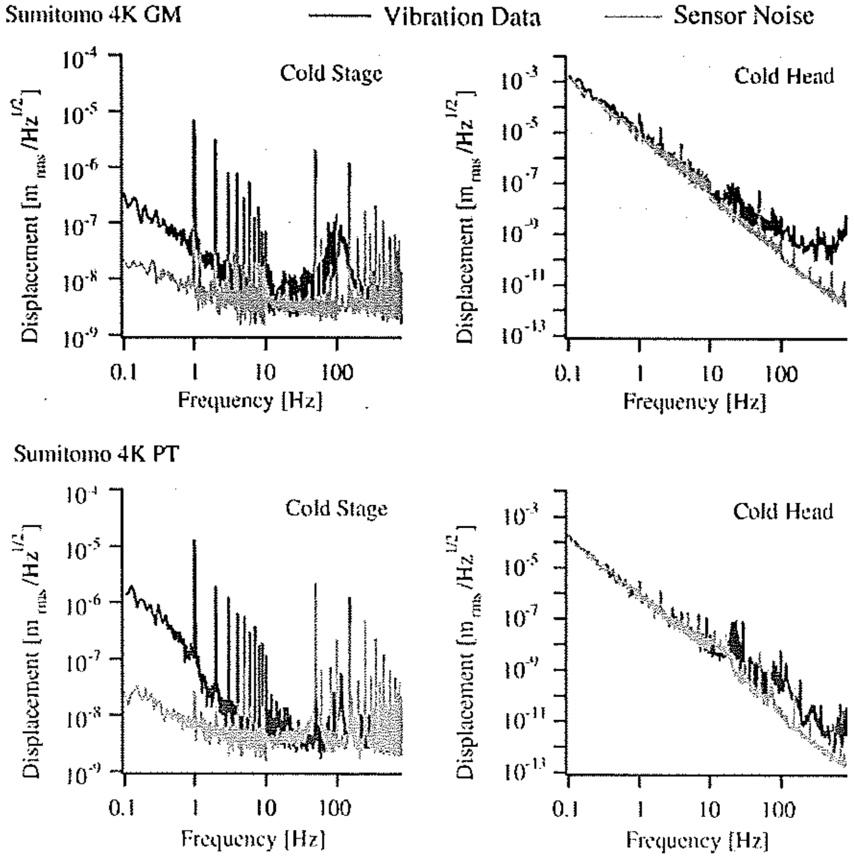

Fig. 6. Horizontal vibration spectra for the 4 K cryocoolers. The blue lines show the sensor-noise-spectra and the red lines show the vibration spectra of the cryocoolers.

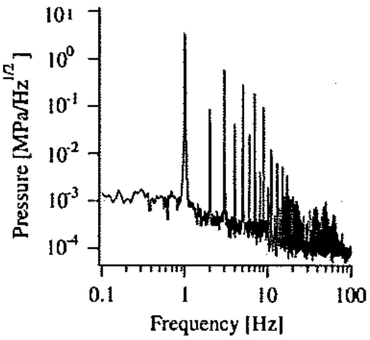

Fig. 7. Vibration spectrum of the pressure of the working gas for the Sumitomo 4 K PT cryocooler.

for both directions were almost the same. Also, other horizontal vibrations (Y direction) were almost the same as that for the X direction for both cryocoolers.

4. Study of the cold-stage vibration

The PT cryocoolers had smaller vibration for the cold-head than the GM. However, the cold-stage vibrations were at the same level for both cryocoolers. Therefore, it is important to understand the vibration mechanism of the cold-stage in order to develop smaller vibration cryocoolers.

Firstly, we simulated an elastic deformation of the pulse-tube (cylinder) by using the finite-element method (FEM). We assumed that the pulse-tube (cylinder) was a stainless-steel pipe of 20 mm in outer diameter, 280 mm in length and 0.25 mm in thickness, and the cold-stage was a copper plate of 86 mm in diameter and 20 mm in thickness. From the simulated result, we confirmed that the pulse-tube (cylinder) stretched as 22 μm when a static pressure of 2 MPa was applied to its inside. This value is almost the same as the measured vibration amplitude. Also, this result is consistent with a simple analytic calculation.

Next, we measured the spectrum of the pressure oscillation of the working gas in the outlet of the rotary valve unit for the Sumitomo 4 K PT cryocooler. Fig. 7 shows the measured spectrum. We confirmed that the spectrum of the pressure oscillation of working gas was similar to that of the cold-stage vibration.

From the above, we concluded that the vibration of the cold-stage with the driving frequency came from an elastic deformation of the pulse-tube (cylinder) by pressure oscillation of working gas.

5. Conclusion

We measured and analyzed the vibrations of the GM and PT cryocoolers by using newly developed vibration measurement method. From the measured results, we found that the difference of the vibrations between the GM and PT cryocoolers did not come from the cold-stage vibration, but from the cold-head vibration. Especially, the vertical vibration of the cold-head for the 4 K GM cryocooler was large, and its acceleration was two orders of magnitude larger than that of the 4 K PT. The vibrational frequency-range was over 10 Hz.

On the other hand, the cold-stage vibrations for the 4 K GM and 4 K PT cryocoolers were same level. From the FEM simulation and the spectrum of the pressure oscillation of working gas, we found that the cold-stage vibrations came from an elastic deformation of the pulse-tube (cylinder), and the vibrations were an essential problem for cryocoolers by using pressure oscillation of the working gas.

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Appendix A. Thermal contraction and tilt of the pulse-tube (cylinder)

During cooling down of the cold-stage, the contraction and tilt of the pulse-tube (cylinder) caused by thermal stress were observed. The measured results are listed in Table 4. The contraction of the pulse-tube (cylinder) was 1.2 mm for both the 4 K GM and 4 K PT cryocoolers. The tilt of the pulse-tube for the 4 K PT cryocooler, which has a complex arrangement of the tubes, was larger than that of the GM, and the displacement was 0.5 mm for the X direction and 0.6 mm for the Y direction.

Appendix B. "Vibration-free" cryocooler

In developing small vibration cryocoolers, there is a question as to how small the vibration of the cryocooler

Table 4
Thermal contraction and tilt of the pulse tube (cylinder)

	X (mm)	Y (mm)	Z (mm)
Sumitomo 4 K GM	–	0.1	1.2
Sumitomo 4 K PT	0.5	0.6	1.2

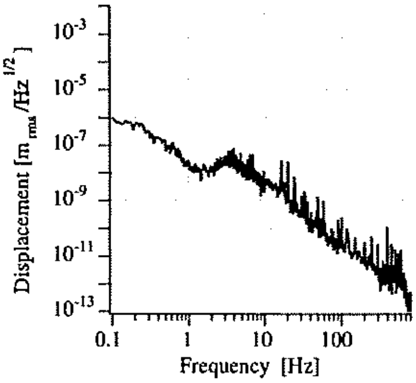

Fig. 8. Seismic vibration-spectrum measured at the Cryogenics Science Center of KEK at night. The peak around 3 Hz corresponds to the resonance of the Kanto-Loam layer around the Tokyo area.

can be said to be "vibration-free". Generally, there is an unfeelingly small seismic vibration around us, and it is known that the spectrum of the seismic vibration in a quiet urban area is described as $\tilde{x}(f) \approx 10^{-7}/f^2$ (m/Hz$^{1/2}$) over a few hertz. Fig. 8 shows a vertical seismic vibration spectrum in KEK at night, measured by a laser accelerometer. A peak around 3 Hz came from the resonance of Kanto-Loam layer around the Tokyo area in Japan. Incidentally, it is known that the seismic vibration in Kamioka mine, which is the site where a large-scale cryogenic gravitational wave telescope (LCGT) [1] will be constructed, is two orders of magnitude smaller than that in a typical urban areas. As the mentioned above, we can not avoid vibrations of cryocoolers and cryogenic systems caused by seismic vibration unless we use special surroundings and vibration-isolators. Therefore, when a cryocooler with seismic vibration level is developed, we can say it is "vibration-free" in general use.

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Characteristics of 4 K pulse tube cryocoolers in applications

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Cryomech has developed and commercialized 4 K pulse tube cryocoolers, Models PT403, PT405, PT407 and PT410, which provide cooling capacities from 0.25 W to 1.0 W at 4.2K. The latest developments at Cryomech enabled the pulse tube cryocoolers to have almost the same capacity and efficiency as GM cryocoolers. The pulse tube cryocoolers have opened many applications and demonstrated their advanced features with respect to long meantime between maintenance, very low vibration and small magnetic field distortion from rare earth materials.

INTRODUCTION

The 4 K pulse tube cryocooler is a new generation of cryo-refrigeration system that can provide cooling capacities below 4 K. It has no moving parts at cryogenic temperatures and leads to advanced features over the 4 K GM cryocooler.

Cryomech, Inc. commercialized the world's first 4 K pulse tube cryocooler, Model PT405 in 1999[1]. In recent years, we have continually developed and commercialized a series of 4 K pulse tube cryocoolers, Models PT403, PT407 and PT410 that provide cooling capacity from 0.25 W to 1.0 W at 4.2 K[2]. These 4 K pulse tube cryocoolers have opened many challenging applications in cooling NMR and MRI magnets, precooling dilution refrigerator, ADR and sorption cooler, cooling sensitive devices like SQUID magnetometer, etc. These applications demonstrate great advantages of pulse tube cryocoolers over GM cryocoolers in the field.

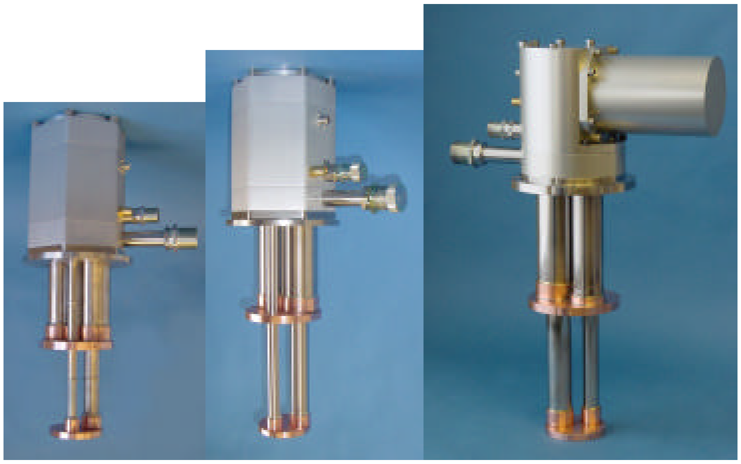
This paper introduces the Cryomech 4 K pulse tube cryocoolers and their performances. The characteristics of the cryocoolers in applications are presented and compared with 4 K GM cryocoolers.

4 K PULSE TUBE CRYOCOOLERS

Figure 1 shows photographs of the 4 K pulse tube cryocoolers, Models PT403, PT405, PT407 and PT410. The configurations of them have been described in reference 1. The PT405 has the same layout geometry as the PT407. Their specifications are given in Table 1.

It has been confirmed that the vibrations in the pulse tube cold heads mainly come from the stretching of the tubes generated by gas compression and expansion[2]. The rotary valve and motor have been integrated in the warm end for the standard cold heads. A special version with a remote rotary valve has also been developed for all of our two-stage pulse tube cryocoolers. In this version (see Figure 2), the rotary valve and motor is separated from the pulse tube expander by 3 feet through a S.S. flexible line. An electrical isolator made of non-metal material is mounted between the rotary valve and the S.S. flexible line to isolate the EMI and RF noise from the driving motor for the rotary valve. The performance of this split version is approximately 5% less than that of the standard integrated version. These split 4 K pulse tube cryocoolers are used for cooling sensitive devices, such as SQUIDs magnetometer, etc.

The 10 K pulse tube cryocoolers developed at Cryomech have achieved the same cooling capacity and efficiency as the 10 K GM cryocoolers[3]. The latest improvements on a laboratory PT410 increases its performance to 1.2W@4.2K and 45W@40K simultaneously for 7.8 kW power input. This unit provides almost the same capacity and efficiency as the 4 K GM cryocooler. This performance will enable the pulse tube cryocooler to replace the GM cryocoolers in many applications in the near future.



PT403 PT405/PT407 PT410

Figure 1. Photographs of the 4 K pulse tube cryocoolers

Table 1. Specifications of the 4 K pulse tube cryocoolers

	PT403	PT405	PT407	PT410
Specification	0.25W@4.2K & 10W@65K	0.5W@4.2K & 30W@65K	0.7W@4.2K & 30W@55K	1.0W@4.2K & 40W@45K
Power input	1 phase, 3 kW	3 phase, 4.6 kW	3 phase, 7 kW	3 phase, 8 kW

Figure 2. PT405/PT407 with remote rotary valve/motor

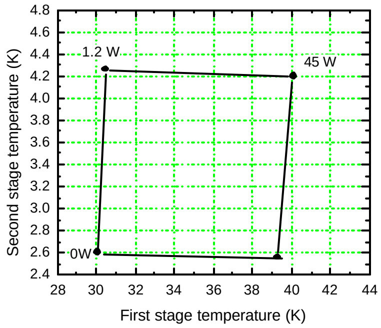


Figure 3. Latest performance of PT410

CHARACTERISTICS OF THE 4 K PULSE TUBE CRYOCOOLER

The 4 K pulse tube cryocoolers demonstrated their advanced features in the applications when compared with the 4 K GM cryocoolers. These features are presented below.

Magnetic field distortion

Small magnetic field distortion from the 4 K pulse tube cryocooler was found in NMR, MRI and SQUIDs systems. The amplitude of the magnetic distortion is approximately 20 nT compared to that of 200 nT from a SHI-SRDK408 4 K GM cryocooler. This magnetic field distortion is caused by the rare earth regenerative materials in the 2nd stage regenerator. Figure 4 shows the variations of magnetization of the rare earth materials of $HoCu_2$ and Er_3Ni at different temperatures. The rare earth materials were put into a very sensitive solenoid to measure their magnetization at external magnetic field of 0.1 Oe and 1 Oe. There are temperature oscillations of 2nd stage regenerative materials at the same frequency of refrigeration. The temperature oscillation could be a few Kelvins[4] and generate a magnetic field fluctuation. This is schematically shown in Figure 5 (a). For a 4 K GM cryocooler (Figure 5 (b)), the magnetic field distortions are generated not only by the temperature swing, but also the motion of the rare earth materials with the displacer. The magnetic field distortion from a 4 K GM cryocooler is normally ten times higher than that from a 4 K pulse tube cryocooler.

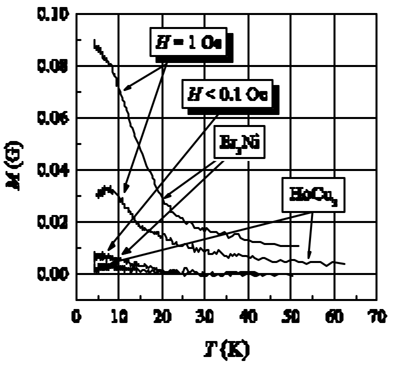
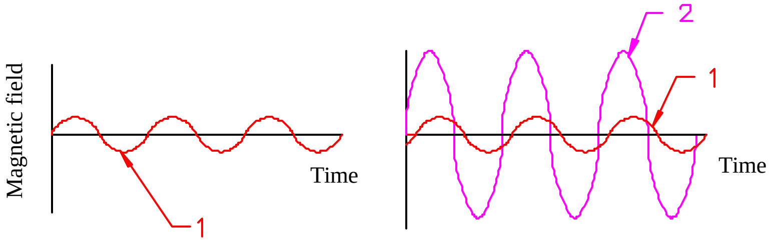


Figure 4. Magnetization of the rare earth materials of HoCu2 and Er3Ni

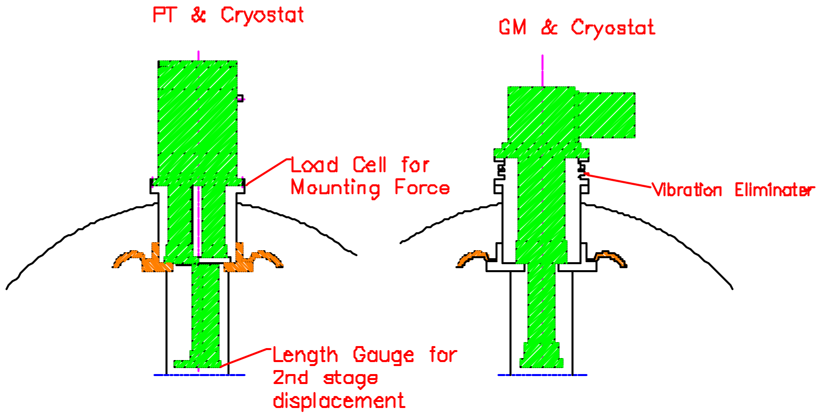


(a) Pulse tube (b) GM

Figure 5. Magnetic field fluctuation generated by the cryocoolers. 1. generated by temperature oscillation; 2. generated by motion of the GM displacer.

Vibration

Figure 6 shows the installation of the pulse tube and GM cryocooler on the cryostat. Vibration of 4 K pulse tube cryocooler is so small that in most applications it can be directly mounted on the cryostat.



(a) (b)

Figure 6 Installation of PT and GM cryocoolers on cryostat

Table 2. Vibration from PT and GM cryocooler

	Mounting force (amplitude)	2^{nd} stage displacement (amplitude)
4 K GM cryocooler (SRDK408)	38 Lb	42 μm
4 K PT cryocooler (PT405)	1.0 Lb	11 μm

For example, a PT405 pulse tube cryocooler was installed in a MRI cryostat. Spin echo testing was performed on it to check the various methods of vibration isolation used for the GM cryocooler before (see Figure 6 (b)). No vibration isolation methods were necessary for the Pulse Tube cooled MRI magnet. No magnetic fluctuations that come from vibration have been observed when directly mounting the pulse tube cryocooler on the MRI cryostat.

The vibration of PT and GM cryocoolers are compared and given in Table 2. A load cell, mounted under the room temperature flanges of the cryocoolers (see figure 6(a)), is used to measure the mounting force. A length gauge which contacts the bottom of the 2^{nd} stage heat exchanger measures the displacement. The mounting force from the 4 K GM cryocooler is 38 times that of the 4 K pulse tube cryocooler, and the displacement is 4 times greater.

Meantime between maintenance (MTBM)

Currently, the maintenance interval of the 4 K GM cryocooler is ~10,000 hours. Cryomech's goal is to provide the 4 K pulse tube cryocooler with MTBM > 5 years (43,800 hours). Three possible service requirements for the 4 K Pulse Tubes in 5 years were investigated and given below.

1. Adsorber in the compressor package. The lifetime of the adsorber is mainly determined by the oil carryover which passes through the oil separator and reaches the adsorber. Figure 7 shows the oil carryover in the CP900 series compressors used for pulse tube cryocoolers. The CP900s are controlled to

have oil carryover of less than 80 mg/day (29 g/year). The adsorbers for the CP900s have been tested and have an ability to adsorb > 300 g oil. It ensures system operation for more than 5 years without service.

2. Lifetime of rotary valve and valve plate in the cold head. The rotary valve and valve plate in the pulse tube cryocooler have less wear since there are no wear particles generated from displacer seals in the GM cryocooler. The valve and valve plate material have been studied and selected. It was found that there was only 0.03 mm wearing away for the valve and no significant wear on the valve plate after 12,000 hours running. We predict that the valve and valve plate will last more than 5 years.

3. Contamination in the cold head. Impact of air contamination in a PT405 pulse tube cryocooler has been investigated and shown in Figure 8. The pulse tube cryocooler has less sensitivity than GM cryocoolers to air contamination (78% N_2, 20% O_2). After adding 600 Torr·Liter air in the system, the first stage lost 2W at the temperature of 65 K and the 2nd stage temperature increased by 0.1 K. This feature enables the pulse tube cryocooler to operate for a long time without needing cold head service.

Since the first PT405 pulse tube cryocooler was delivered to a user in July 1999, a few hundred pulse tube cryocoolers are working in the field. Many of them have operated for 15,000~25,000 hours. So far, there has been no report on the performance degradation of our pulse tube cryocoolers. All of this information supports us toward our goal of providing the Pulse Tubes with 5 years MTBM.

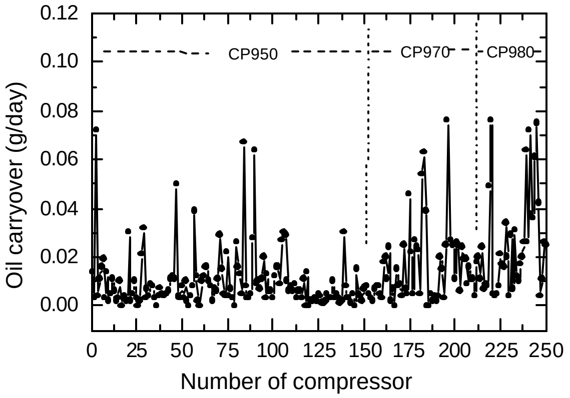


Figure 7 Oil carryover in CP900 series compressor

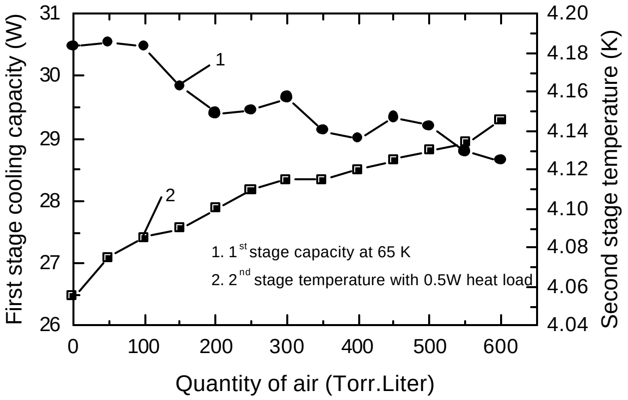


Figure 8. Impact of air contamination in the PT405

CONCLUSION

Cryomech has developed and commercialized 4 K pulse tube cryocoolers to provide cooling capacities from 0.25 W to 1.0W at 4.2K. The 4 K pulse tube cryocoolers have opened many challenging applications and demonstrated their advanced features with respect to very low vibration, low magnetic field distortion and long MTBM.

ACKNOWLEDGMENT

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