EXPERIMENTS WITH LINEAR COMPRESSORS FOR PHASE SHIFTING IN PULSE TUBE CRYOCOOLERS

M. A. Lewis, P. E. Bradley, and R. Radebaugh

National Institute of Standards and Technology
Boulder, Colorado 80305 U.S.A.

ABSTRACT

For the past year NIST has been investigating the use of mechanical phase shifters as warm expanders for pulse tube cryocoolers. Unlike inertance tubes, which have a limited phase shifting ability at low acoustic powers, mechanical phase shifters have the ability to provide nearly any phase angle between the mass flow and the pressure. We discuss our results with experiments and modeling on a commercially available miniature linear compressor operating as an expander on the warm-end of a 4 K pulse tube, whose temperature is nominally about 35 K. We also present results on experiments with a linear compressor operating at room temperature but coupled to the 4 K stage through secondary regenerators and secondary pulse tubes. Experiments on a small pulse tube test apparatus with both ^{4}He and ^{3}He showed improved efficiency when using the mechanical expander over that of inertance tubes. Phase locking techniques using function generators and power amplifiers for control of phase angle are detailed. The use of expanders demonstrates flexible control in optimizing phase angles for improved cryocooler performance.

KEYWORDS: Cryocooler, expander, mechanical phase shifter, phase angle, secondary pulse tube, and secondary regenerator.

INTRODUCTION

Phase Shifters

Cryocoolers are commonly used commercially and for space and military applications for low temperature cooling, particularly in the area of low temperature superconductors (LTS). For LTS applications, small scale cryocoolers are of interest, and temperatures of about 4 K are desired. The typical types of cryocooler used for these applications is the Gifford-McMahon (GM) or GM-type pulse tube, which operate at frequencies at about 1 Hz with very low efficiency, in addition to being large, noisy and using high input powers

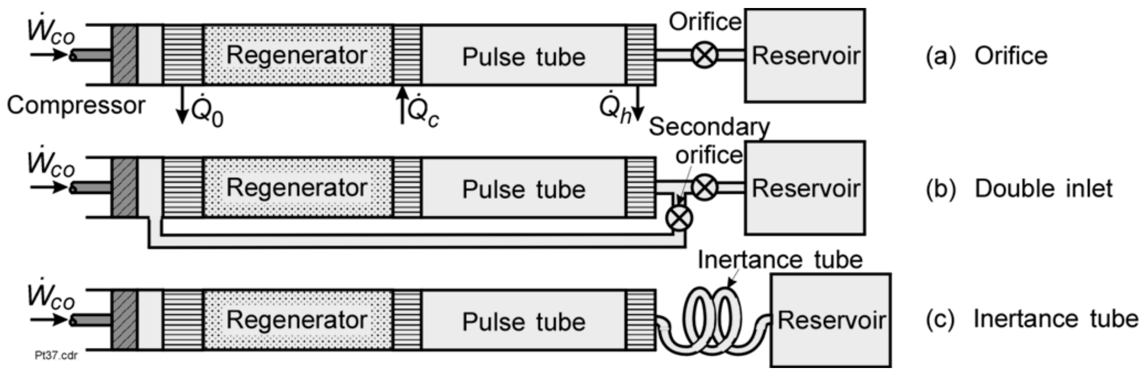


Figure 1. Schematics of three common phase shifting methods for pulse tube cryocoolers.

to operate. [1] When these low frequency cryocoolers are used there are inherent temperature oscillations at the cold-end. Increasing cryocooler frequency reduces the amplitude of temperature oscillations seen at the cold-end. The use of higher frequency also is helpful for overall efficiency in converting electrical power into the desired PV power. The transition from 1 Hz frequency too much higher frequencies allows the use of the Stirling and Stirling type pulse tube cryocoolers. Operating at higher frequency ranges, 30 Hz to 60 Hz, leads to greater regenerator losses at 4 K when not operating at ideal conditions. [2] The optimization between the phase angle of the pressure and the flow, where flow lags pressure, is critical at the cold-end of a 4 K cryocooler to provide optimum efficiency. Recent modeling has shown that the optimum phase required at the cold-end is 30°, which would require a 60° phase difference at the pulse tube warm-end. These phase shifts could be accomplished with the use of inertance tubes. The difficulty in creating the large phase shifts needed for this application is that the small refrigeration powers that are being used in 4 K electronic applications do not allow the ability to create sufficient phase shift in inertance tubes. At a frequency of 30 Hz and low temperatures of about 30 K only a few degrees of phase shifting is obtainable with an inertance tube. Other approaches, using double inlet configuration with a secondary orifice between the regenerator and pulse tube warms-ends, create large losses due to lost work in the secondary orifice and DC flow. [3] Figure 1 shows the three most common passive phase shifting methods for pulse tube cryocoolers.

Research has shown that with the use of warm-end expanders or displacers, larger phase shifts can be achieved by use of small acoustic powers.[4-7] Figure 2 shows two types of mechanical phase shift mechanisms that are used in regenerative cryocoolers. Commercially available pressure oscillators can be used for the warm-end expander when the warm-end of the pulse tube operates at ambient temperature. When a pulse tube is to operate at 4 K and high frequency, the warm-end of the pulse tube must operate at about 30

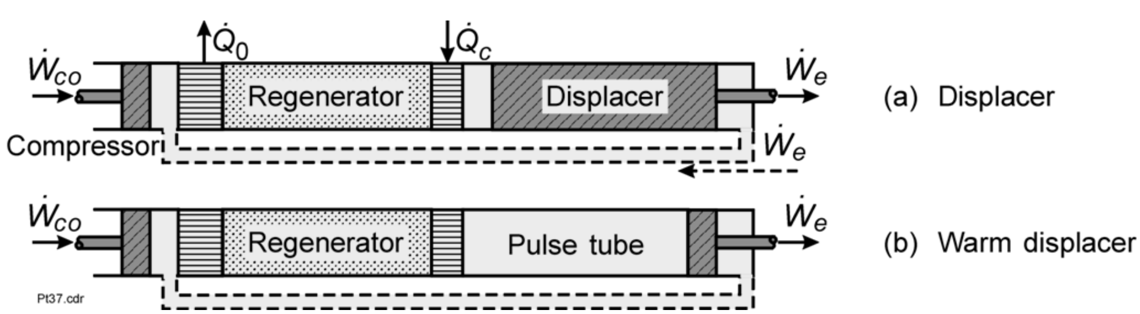
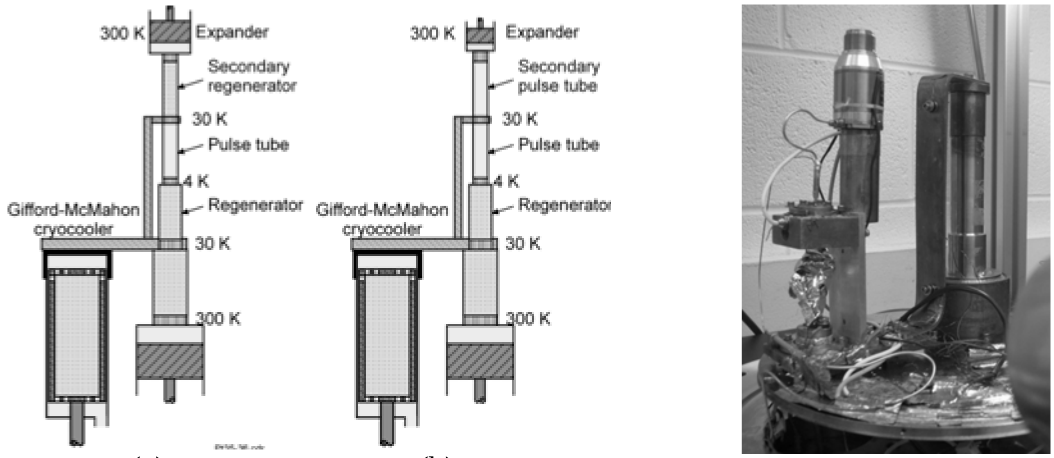


Figure 2. Schematics of mechanical phase shift mechanisms used in regenerative cryocoolers.



(a) (b) (c)

Figure 3. Schematics (a) and (b) that show the use of a secondary regenerator or a secondary pulse tube to couple a room-temperature expander to the warm-end of a 4 K pulse tube cryocooler. Photo (c) show the use of an expander attached to the pulse tube warm-end at 35 K.

K to maintain the proper efficiency needed for the pulse tube operation. This would require the use of a secondary regenerator or secondary pulse tube coupled to the 30 K pulse tube warm-end and the ambient temperature expander. Commercial compressors can still be used at ambient temperatures in such a configuration, as shown in Figures 3a and 3b. We have found at least one commercial linear compressor that operates satisfactorily at temperatures down to 30 K. Such a compressor can be mounted directly on the 30 K warm-end of the pulse tube, as shown in Figure 3c, and used as a mechanical phase shifter or expander.

EXPERIMENTAL PROCEDURES

Apparatus Hardware

The experimental test apparatus consisted of a commercially available 4 K Gifford-McMahon cryocooler that was used to pre-cool a hybrid third stage component. [8] Figures

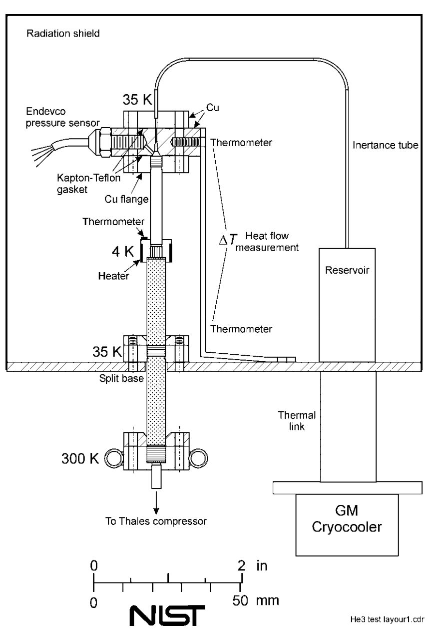


Figure 4. Schematic of experiment apparatus.

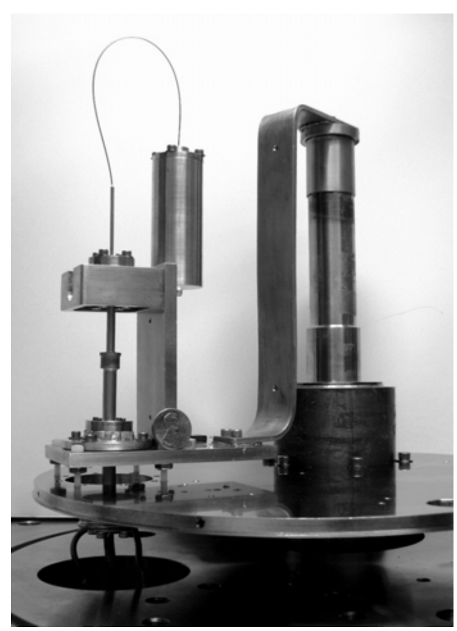


Figure 5. Photo of experiment apparatus.

Figure 6. Single piston linear compressor

4 and 5 show a schematic and photo of the apparatus and its components. The hybrid third stage was driven by a commercially available linear compressor using a flexure bearing design. Figure 5 shows the use of an inertance tube and reservoir at the pulse tube warm-end used in earlier experiments. The inertance tube and reservoir were replaced in these experiments with a commercial linear compressor.

Two different types of expanders were used for these experiments, and are commercially available. The initial experiments used a dual-piston linear compressor outside the vacuum can at room temperature as an expander to generate phase shifting at the warm-end of the pulse tube. It has a maximum swept volume of about 4 cm^3. These experiments utilized a secondary regenerator or a secondary pulse tube to couple the room temperature expander to the 35 K warm-end of the pulse tube designed to operate at 4 K. The second set of experiments used a miniature linear compressor with a single piston design, whose maximum swept volume was 0.57 cm^3. Both the piston and cylinder liners are constructed of M42 steel being hardened to HRc 65, machined to N3 and tightly matched to 4 µm radial clearances. The piston and cylinder liners have the same thermal properties, allowing the compressor to be used as an expander inside the vacuum space and thermally linked to the 35 K warm-end of the pulse tube. This compressor is shown in Figure 6 as part of a split Stirling cryocooler system and previously in Figure 3c as it was used as an expander and thermally anchored to the 35 K copper plate inside the 80 K vacuum radiation shield.

Phase Locking Techniques

The pressure oscillator used to drive the third stage hybrid and the two expanders

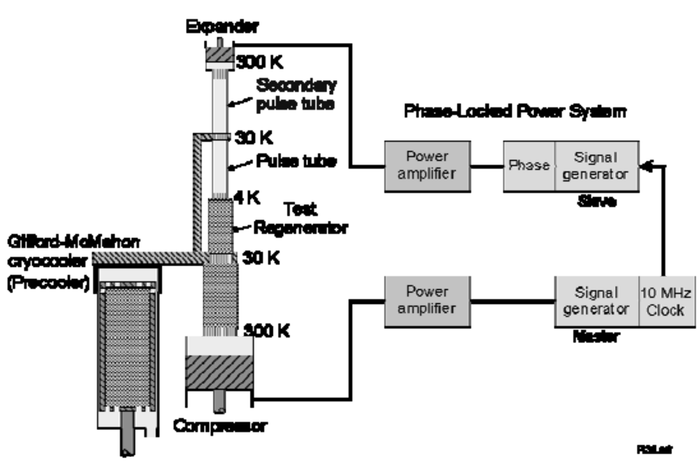


Figure 7. Oscillator and expander phase locking technique.

connected to the hybrid warm-end pulse tube, one located at room temperature or the other at 35 K, were operated at a specific frequency by use of two signal generators. One of the signal generators sent a 10 MHz clock signal to the other in order to phase-lock the two instruments and subsequently phase-lock the pressure oscillator and the expander. These phase-locked signals were amplified with two separate power amplifiers that were used to operate the oscillator and the expander at specified, and separate, electrical input powers. The input power to the system pressure oscillator was typically run at the maximum power of the compressor. The electrical power to the expander was adjusted to obtain specific low end temperature results. Once the input power was set, the phase offset was adjusted to the expander relative to that of the system pressure oscillator. Offset phase angles from 0 to 360 degrees were used in the measurements. Figure 7 shows a schematic of the phase locking technique used for the pressure oscillator and the expander.

Model Procedures and Results

The secondary regenerator and the secondary pulse tube were modeled by the NIST software REGEN3.3 using a finite difference technique to evaluate the four conservation equations in a regenerator. Typically, the model is used for the evaluation of regenerators in cryocoolers, but it was found to be equally good in modeling acoustic power flows in either direction when input conditions were used that address the direction of the acoustic power flow from hot to cold or cold to hot. It was also used to model the secondary pulse tube, but its accuracy in that case may not be so good because it was not designed to deal with high Velenci number. Hydraulic diameters for both the regenerator and the pulse tube were varied by use of typical porosity values of 0.68 for the regenerator and an arbitrary value of 0.91 for the pulse tube, an input value was needed for modeling purposes. Typical regenerators have hydraulic diameters less than 100 µm, which causes rather large swept volume ratios between the warm-end and the cold-end. A pulse tube diameter of 2 mm or larger lowers the swept volume significantly, about 6 times lower. This means that an expander with less swept volume can be used with the secondary pulse tube, compared with the use of a secondary regenerator.

EXPERIMENTAL RESULTS

The experiments consisted of an apparatus that was designed to study and understand the physical phenomena and impact of real gas behavior of the oscillating helium gas, ^{4}He or ^{4}He, at a temperature of about 4 K. The system was designed to thermally link a hybrid third stage to a commercially available 4 K Gifford McMahon cryocooler. The hybrid third stage was thermally linked to the GM cryocooler at the second stage to cool the third stage warmed to about 35 K. The first stage of the GM cryocooler was thermally linked to a radiation shield that provides an 80 K thermal intercept from the 300 K vacuum jacketed chamber.

Experimental tests were performed by use of a pressure oscillator as a room temperature expander, introducing a form of active phase shifting at the warm-end of the pulse tube. In addition to the warm expander, a secondary regenerator and a secondary pulse tube are introduced. The secondary regenerator and secondary pulse tube produce acoustic power from the cold-end to the warm-end, and due to minimum pressure drop through the component has the ability to produce phase shifting at the pulse tube warm-end. The secondary regenerator amplifies the acoustic power proportional to the temperature due to it isothermal behavior. Therefore the volume flow increases with temperature. The secondary pulse tube provides acoustic power from cold to hot with no amplification, due to its nearly adiabatic behavior. The secondary pulse tube is more desirable due to the fact that it requires much smaller swept volumes than the secondary regenerator. [5-8] The secondary regenerator was a stainless steel tube 44.5 mm in length with an inside diameter of 3.40 mm and packed with 200 mesh copper screen with a porosity of about 0.67. The hydraulic diameter was about 0.108 µm. The secondary pulse tube was a stainless steel tube 50.8 mm in length with an inside diameter of 4.30 mm. Each component was thermally linked to the 35 K copper plate inside the 80 K radiation shield during the experimental testing.

The test procedure involved cooling the entire apparatus using the 4 K GM cryocooler and waiting for temperature stabilization. The pressure oscillator for the third stage hybrid was then operated at the maximum allowable value of current. A dual piston pressure oscillator was used as the expander for the first set of experiments. Once the expander was operating, the phase to the expander was offset in increments from 0 to 360 degrees in relation to the pressure oscillator.

The test results for the secondary regenerator showed that as the offset phase was varied at the expander, the cold-end temperature was affected and a minimum temperature of 9.6 K was achieved with ^{4}He as the working fluid. Similar results were achieved using the secondary pulse tube although an improved performance was expected. Additional data with varied secondary pulse tube, aspect ratios may improve the low end performance. Experimental data were taken using a frequency of 16 Hz and 24 Hz, and the results were similar in trends. The average pressure used was 1.0 MPa, with pressure ratios at the compressor being about 1.43 and the pressure ratio at the warm-end of the pulse tube about 1.32.

A commercial pressure oscillator was connected directly to the warm-end of the pulse tube and thermally anchored to the 35 K copper plate inside the apparatus vacuum shield, as shown in Figure 7. The pressure oscillator was electrically controlled and able to provide phase shifting within the bounds of its swept volume and maximum current range. In order to obtain information about the performance of the expander, the voltage and current to the expander were measured along the corresponding phase angle of the voltage and current. This information allowed calculations to obtain PV power at the expander and an understanding of the peak-to-peak stroke of the expander without piston position sensors.[9] The testing procedure involved cooling the apparatus with the 4 K GM cryocooler to the low-end temperature and allowing thermal stability of all the apparatus components. The pressure oscillator of the third stage hybrid was then operated at its maximum current limit to obtain maximum cooling at the cold-end. The cold expander was operated at various levels of input power to observe its effect on low end temperature and on the heating of the expander. The frequency of both the pressure oscillator and the expander were set to the same value and phase-locked using the signal generators. Most measurements were made at 16 Hz, but additional frequencies such as 14 Hz and 30 Hz were also used. Most of the tests were operated at about 1.5 volts rms of electrical power to the expander. This input power had the least effect on the expander warming up over time and allowed the operation of the phase shifting using the signal generators. As the system stabilized, the phase shifting between the pressure oscillator and the expander were adjusted. The phase of the expander, relative to the pressure oscillator, was varied from 0 to 360 degrees. The average pressure was 1.0 MPa for most experimental results, although there were some tests operated at 0.8 MPa. The pressure ratios were about 1.45 at the pressure oscillator and 1.35 at the warm-end of the pulse tube. A low-end temperature of about 9.5 K was obtained, and the effects of the expander on phase shifting and low-end temperature are shown in Figure 8.

The test results showed that the expander phase relative to that of the third stage pressure oscillator has a significant effect on the low-end performance, due to the phase shifting at the warm-end of the pulse tube. As the phase was changed from 0 to 360

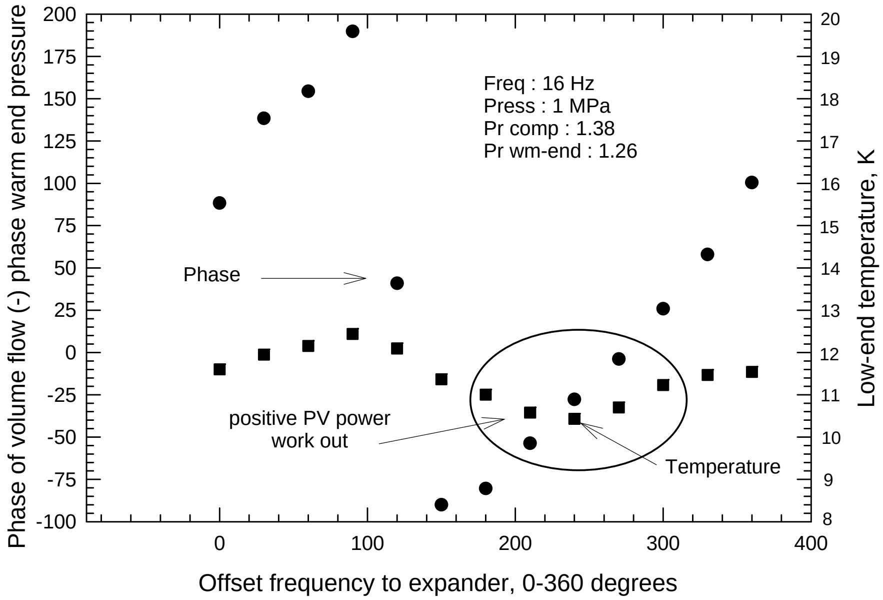


Figure 8. Phase of volume minus phase of pressure relative to offset frequency to expander.

degrees, the low-end temperature varied between 9.5 and 17.5 K. With instrumentation to measure the input voltage and current to the expander, we were able to calculate the PV power being produced and calculate an approximate peak-to-peak stroke for the expander. In the analysis of pulse tube cryocoolers, a positive acoustic power flow is generally meant to be a flow from the compressor to the expander. Maintaining that convention here and consider a positive acoustic power flow to be from the cold-end to the expander, a positive value would signify the providing of expansion power. The PV power values indicated at the low-end temperatures, where the phase relationship provide more efficient operation, the PV power was being removed at the cold-end of the pulse tube and therefore lower temperatures. Figure 8 shows the effect of the phase of the volume flow minus the phase of the pressure as the offset phase to the expander is incrementally changed from 0 to 360 degrees. Positive PV values are achieved where the cold-end of the pulse tube reaches its lowest temperature. The positive PV values indicate that energy is being taken out of the system. In all other areas the PV power values are negative and this indicates that energy is being put into the system.

CONCLUSIONS

Large phase shifts between the flow and the pressure at the cold-end are required when Stirling–type pulse tube cryocoolers are operated at 4 K. Inertance tubes are not capable of providing the phase shifting needed for maximum COP and efficiency to operate at these low temperatures. In order to achieve the large phase shifting needed at the warm-end of the pulse tube commercially available linear compressors can be used as expanders to create the desired phase shifts. Most linear compressors are designed to operate at room temperatures, therefore secondary regenerators and secondary pulse tubes are used between the warm-end of the pulse tube, at about 30 K, and the room temperature compressor. A commercially available compressor was shown to operate successfully when mounted at the warm-end of the pulse tube and operated at 35 K. This provides phase shifting without the need for secondary regenerators or pulse tubes. Measurement techniques were used to analyze the phase components of voltage and current to the expander located at the 35 K warm-end of the pulse tube. The results provide information into the peak-to-peak piston displacement without the use of piston position sensors. Additional experiments need to be completed to validate the results achieved, although the methodology provides the ability to make measurements that will ultimately provide knowledge of the piston displacement.

ACKNOWLEDGEMENTS

This research was partially funded by the Office of Naval Research with Deborah Van Vechten as the project monitor.

REFERENCES

1. Radebaugh, R., "Refrigeration for Superconductors," *Proc. IEEE, Special Issue on Applications of Superconductivity*, vol. 92, (2004), pp. 1719-1734.
2. Radebaugh, R., Huang, Y., O'Gallagher, A., and Gary, J., "Optimization Calculations for a 30 Hz 4 K Regenerator with Helium-3 Working Fluid," *Adv. Cryogenic Engineering*, Vol 55, Amer. Inst. of Physics, New York, 2010, pp. 1581-1592.
3. Gedeon, D., "DC Gas Flows in Stirling and Pulse Tube Cryocoolers," *Cryocoolers 9*, Plenum Press, New York, 1997, pp. 385-392.
4. Matsubara, Y., and Miyake, A., "Alternative Methods of the Orifice Pulse Tube Refrigerator," Proc. 5th International Cryocooler Conference, Monterey, CA, 1988, pp. 127-135.
5. Ishizaki, Y., and Ishizaki, E., "Prototype of Pulse Tube Refrigerator for Practical Use," *Adv. Cryogenic Engineering*, Vol. 39, Plenum Press, New York, 1994, pp. 1433-1439.
6. Brito, M.C., and Peskett, G.D., "Experimental analysis of free warm expander pulse tube," *Cryogenics* 41, 2001, pp. 757-762.
7. Zhu, S., and Nogawa, M., "Pulse tube Stirling machine with warm gas-driven displacer," *Cryogenics* 50, 2010, pp. 320-330.
8. Garaway, I., Lewis, M. Bradley, P., and Radebaugh, R., "Measured and Calculated Performance of a High Frequency, 4 K stage, He-3 Regenerator," *Cryocoolers 16*, II Press, Boulder, Colorado,2011,pp. 405-410.
9. Doubrousky, V. Veprik, A., and Pundak, "Sensorless Balancing of a Dual-Piston Linear Compressor of a Stirling Cryogenic Cooler," Cryocoolers 13, Sprinker, New York, 2004, pp. 231-240.