Energy Efficient Operation of 4 K Pulse Tube Cryocoolers

C. Wang, A. Beyer, J. Cosco, B. Lichtenwalter and E. Brown

Cryomech, Inc., Syracuse, NY 13211, USA

ABSTRACT

An inverter compressor has been developed and commercialized for driving 4 K pulse tube cryocoolers; Cryomech models PT410 (1 W at 4.2 K) and PT407 (0.7 W at 4.2 K). Both cryocoolers have operated successfully with input power frequencies from 30 Hz to 62Hz. The PT410 provides 0.2 W to 1.1 W at 4.2 K and the PT407 provides 0.22 W to 0.78 W at 4.2 K in the tested frequency range. A new generation helium reliquefier and small liquid helium plant operate with the inverter compressor in an intelligent, pressure feedback mode to match the cold head capacity to the thermal load from liquid helium boil-off. The intelligent operation mode can reduce the power consumption of these devices by up to 50% in some applications. Field testing of a limited number of 4 K pulse tube cryocoolers driven by inverter compressors is currently underway.

INTRODUCTION

Commercial 4 K Gifford-McMahon (GM) and pulse tube cryocooler compressors operate at a fixed speed that results in a constant 4 K cooling capacity[1,2]. The cryocooler's capacity is typically selected to exceed the peak cryogenic thermal load that the user expects from their equipment to ensure that the system still provides sufficient refrigeration after years of operation and associated performance degradation. To correct for the excess refrigeration, heat is applied to the cryocooler via a resistive heater which is connected to a temperature controller. This solution is effective at maintaining temperature, but the compressor input power used to produce the excess 4 K cooling capacity is wasted.

The potential for energy savings by reducing cryocooler capacity to match the cryogenic thermal load is presented by Sayles et al[3]. A 4 K GM cryocooler was designed that used an inverter compressor for cooling a cryogen-free physical property measurement instrument.

Intelligent operation of a 4 K pulse tube cryocooler using an inverter compressor to match the cryocooler capacity to the thermal load was introduced at Cryomech, Inc.[4] During the development, three Cryomech compressor models were tested with the inverter. Compressor performance was continuously investigated and electromagnetic noise from the inverter was reduced. The result of this research is the model CP287i compressor. It is the first commercially available inverter compressor for 4 K pulse tube cryocoolers and is currently undergoing field trials.

Cryocoolers 18, edited by S.D. Miller and R.G. Ross, Jr.

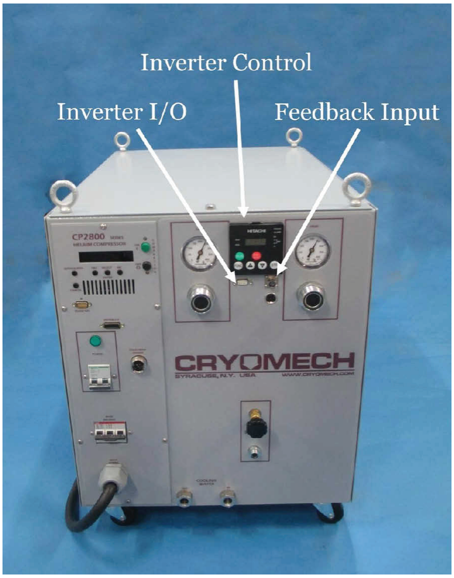

Figure 1. Photo of the inverter compressor, model CP287i

In this paper, we will present the results of the CP287i operating with the PT410 (1 W @ 4.2 K) and the PT407 (0.7 W @ 4.2 K) cryocoolers. Applications of the PT410 cryocooler for helium reliquefiers and liquid helium plants are presented in this paper.

INVERTER COMPRESSOR CP287i

4 K cryocoolers normally operate with 50 or 60 Hz input power. The model CP287i inverter driven compressor varies compressor speed by varying input power frequency from 30 to 65 Hz. The CP287i is designed for driving both the Cryomech PT410 and PT407 cold heads. Figure 1 shows a photo of the CP287i. On the front panel of the new generation compressor there are two inverter interface ports and a control pad. The control pad can be used for manually adjusting the speed of the compressor. A feedback input port is used to connect the transducers for feedback control of cryostat parameters such as pressure or temperature. An inverter I/O port is used for remotely controlling or monitoring the operation of the inverter.

EXPERIMENTAL RESULTS AND ANALYSIS

Performance of 4 K Pulse Tube Cryocoolers with CP287i

The performance of the PT410 cold head with CP287i compressor is shown in Figure 2. At an input power frequency of 60 Hz, the PT410 provided 50 W of cooling at 45 K on the 1st stage and 1.1 W of cooling at 4.15 K on the second stage. At an input power frequency of 30 Hz, the PT410 provided 12 W at 45 K on the 1st stage and 0.2 W at 4.15 K on the second stage. The 1st stage capacity at 45 K was approximately linear, however the 2nd stage capacity at 4.15 K exhibited some non-linearity, decreasing slowly from 62 to 45 Hz and then quickly from 45 to 30 Hz.

Figure 3 shows the effect of the inverter input power frequency on the CP287i compressor power consumption when used with the PT410 cryocooler. The CP287i compressor drew 7.9 kW with the PT410 during 60 Hz operation. Power consumption was reduced to 3.4 kW when the CP287i was used with the PT410 at 30 Hz. The decrease in power consumption with decreasing input power frequency was approximately linear.

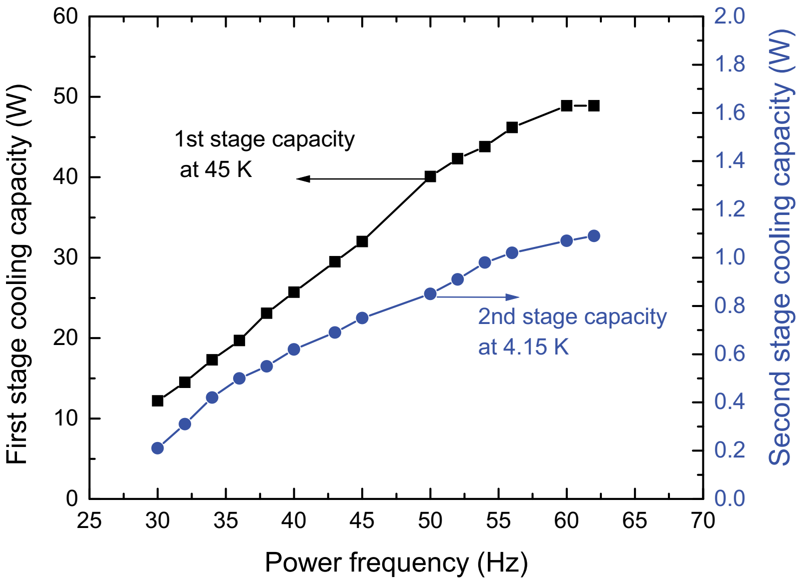

Figure 2. PT410 cooling capacities vs. power frequency

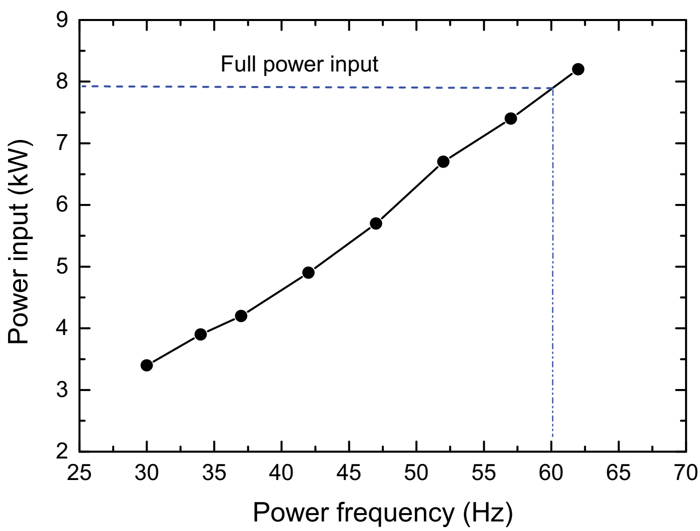

Figure 3. PT410 power consumption vs. power frequency

The performance of the PT407 cold head with CP287i compressor is shown in Figure 4. At an input power frequency of 60 Hz, the PT407 provided 32 W at 55 K on the 1st stage and 0.78 W at 4.2 K on the second stage. At an input power frequency of 30 Hz, the PT407 provided 13 W at 55 K on the 1st stage and 0.22 W at 4.15 K on the second stage. The PT407 with the CP287i compressor was tested at 62 Hz. The 1st stage capacity at 45 K exhibited some non linearity decreasing slowly from 60 to 50 Hz then quickly from 50 Hz to 30 Hz. The 2nd stage capacity at 4.15 K was highly non-linear and decreased very slowly from 60 Hz to 42.5 Hz, then rapidly from 42.5 to 30 Hz.

Figure 5 shows the affect of inverter input power frequency on CP287i compressor power consumption when used with the PT407 cryocooler. The CP287i compressor drew 6.8 kW with the PT407 during 60 Hz operation. Power consumption was reduced to 2.9 kW when the CP287i was used with the PT407 at 30 Hz. Similar to the operation of the CP287i with the PT410, the decrease in power consumption with decreasing input power frequency was approximately linear.

Figure 6 shows the coefficient of performance of the PT407 as a function of power frequency. The gradual, nonlinear decrease in second stage cooling capacity from 60 Hz to 40 Hz and the linear decrease in power consumption with decreasing frequency resulted in a peak in coefficient of performance at 42.5 Hz. The coefficient of performance didn't drop below the 60 Hz value until the input power frequency was lower than 35 Hz. This demonstrates that efficient operation of the PT407 with CP287i compressor is possible across a wide range of operating frequencies.

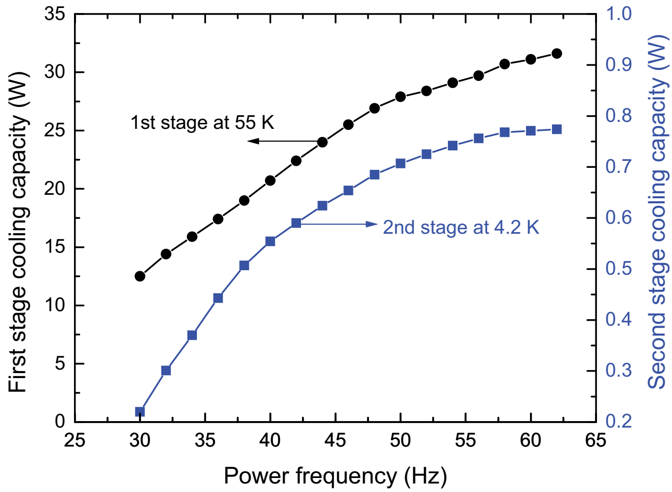

Figure 4. PT407 cooling capacities with different power input

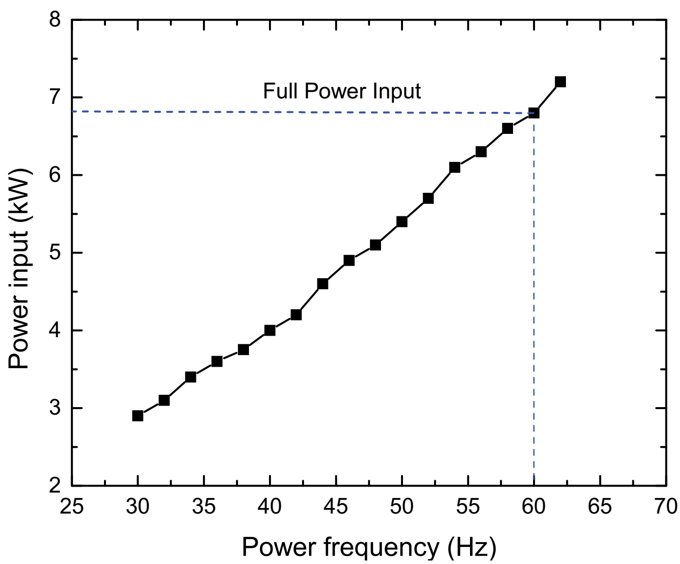

Figure 5. PT407 power consumption vs. power frequency

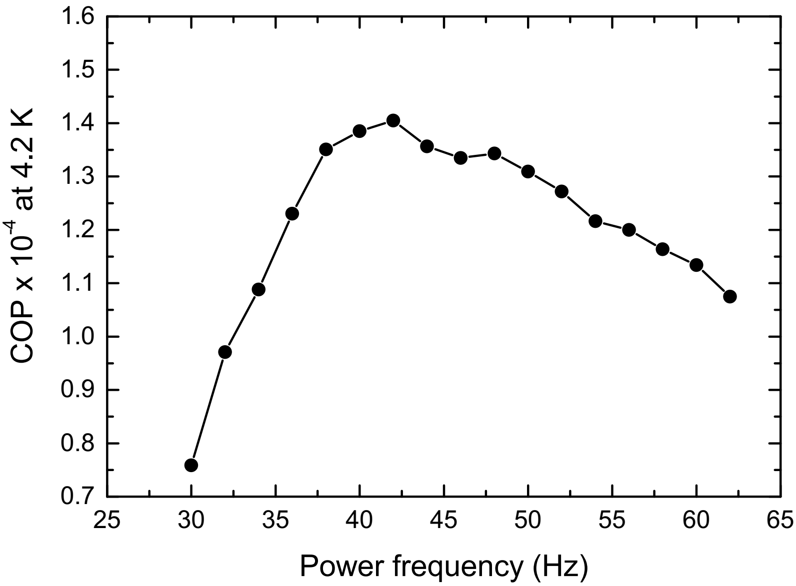

Figure 6. PT407 COP at 4.2 K vs. power frequency

Energy Saving Operation of new PT410 Reliquefier with CP287i

A helium reliquefier built around a 4 K pulse tube cryocooler PT410 has been introduced by Wang[5]. The reliquefier creates a closed-loop for helium boil-off thereby eliminating the need to refill the cryostats with liquid helium.

Figure 7 shows a schematic of the reliquefier using the intelligent CP287i compressor with a liquid helium cryostat. A pressure transducer connected to the inverter in the CP287i compressor monitors the vapor pressure in the cryostat. The inverter uses the pressure signal in a feedback loop to maintain the vapor pressure in the Dewar at a user defined set point by adjusting the compressor input power frequency. For a high thermal load, the inverter increases the compressor speed to prevent loss of helium. Likewise for a low thermal load, the inverter slows the compressor to minimize power consumption.

In testing, varying heat loads were applied to liquid helium in a cryostat to simulate different boil-off rates. Figure 8 shows the results of this testing. The CP287i compressor with the PT410 reliquefier was able to reliquify up to 26.6 L/day with 7.5 kW of power consumption or as little as 3.3 L/day with 4.7 kW of power consumption.

The CP287i compressor quickly and automatically changed speed to match the varying loads with only minimal deviation from the pressure set point. Besides energy saving, another added benefit of the CP287i is that it eliminates the need for a temperature controller to maintain pressure in the Dewar. A less costly temperature monitor is provided with the system so that the user can monitor the 2nd stage temperature of the pulse tube cryocooler.

New Generation of Small Helium Liquefier with CP287i

A new generation liquid helium plant, model LHeP15, incorporating the intelligent operation features of the CP287i is shown in a direct recovery application in Figure 9. The touch screen computer provides remote monitoring and control of the system from anywhere in the world via an internet connection. For direct recovery from a cryostat, the cryostat boil-off is

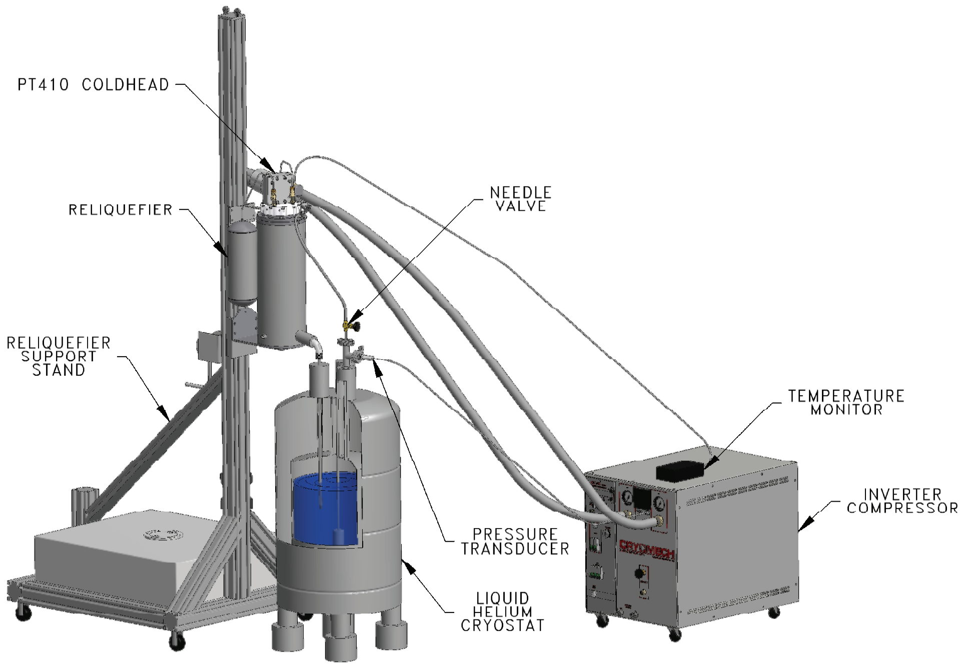

Figure 7. Schematic of PT410 reliquefier with CP287i

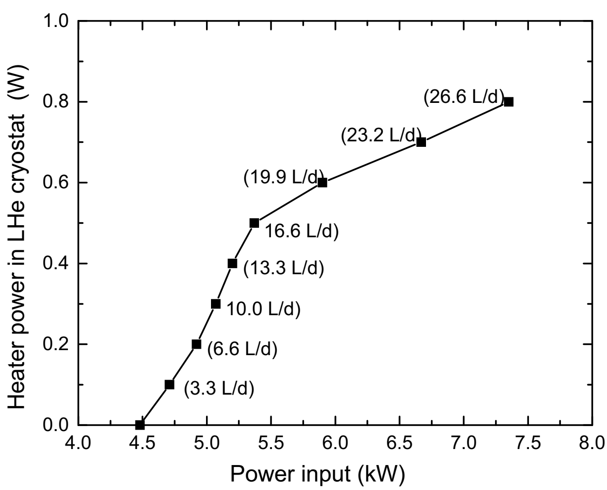

Figure 8. Variation of reliquefier input power with liquid helium boil-off rate in liters/day (L/day)

routed directly into the gas inlet of the liquid helium plant to be reliquefied. The new generation LHeP15 incorporates the CP287i and a pressure transducer to regulate the input power frequency so that the liquefaction capacity of the liquid helium plant matches the boil-off rate. Figure 10 shows the power consumption and input power frequency of the LHeP15 for different helium boil-off rates. Depending on the user's boil-off rate and cost of electricity, the new generation LHeP15 could save up to $10,000/yr on electricity costs.

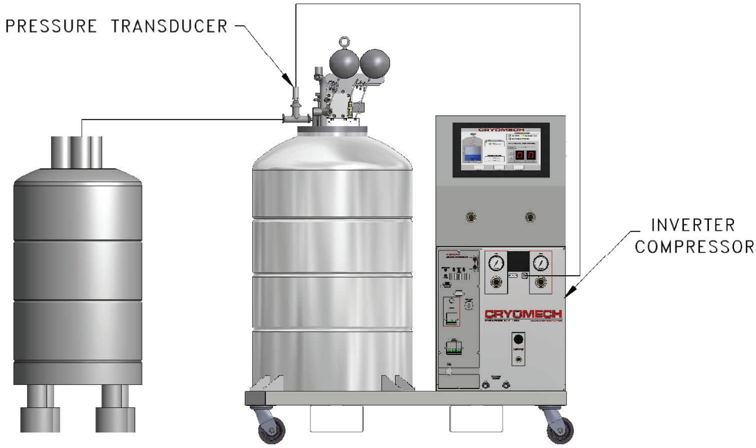

Figure 9. Schematic of new generation helium liquefier in direct recovery application

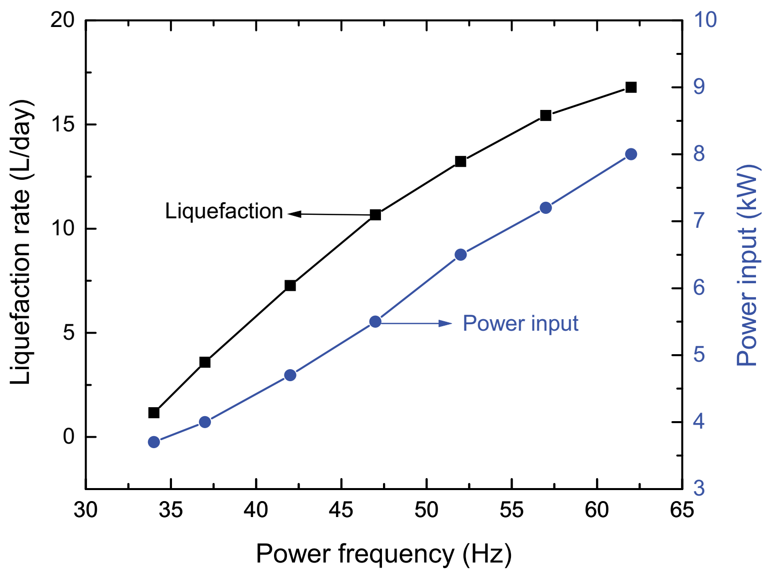

Figure 10. Power frequency of the LHeP15 vs. liquid boil off in the user's cryostat

CONCLUSION

Two different 4 K pulse tube cryocooler models have been operated successfully with a newly developed inverter compressor for energy efficient operations. A new generation helium reliquefier and small liquid helium plant have integrated the inverter compressor and a model PT410 cryocooler. Field trials of the intelligent compressor and 4 K pulse tube cryocoolers are underway.

REFERENCES

1. Catalog from Sumitomo Heavy Industries., 1-1 Osaki, 2-Chrome, Shinagawa-Ku, Japan.
2. Catalog from Cryomech, Inc., 113 Falso Drive, Syracuse, NY, USA.

3. Sayles, T., Martien, D., and Diederichs, J., et al, "Enhanced Helium Compressor Operation for Sensitive Measuring Instrumentation," *Cryocoolers 16,* ICC Press, Boulder, CO (2011), pp. 371-373.

4. Wang, C., "Dynamic Operation of a 4K Pulse Tube Cryocooler with Inverter Compressor," *Cryocoolers 16,* ICC Press, Boulder, CO (2011), pp. 63-70.

5. Wang, C., “A Helium Re-Liquefier for Recovering and Liquefying Helium Vapor From Cryostat,” *Adv. in Cryogenic Engineering*, Vol. 55A, Amer. Inst. of Physics, Melville, New York (2010), pp.687-694.