Results from a Year of Running a 12 L Per Hour Pulse Tube Liquefier in an Industrial Application

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ABSTRACT

Callaghan Innovation and Fabrum Solutions, in collaboration with Absolut System, have produced a range of large pulse tube cryocoolers. The cryocoolers are based on Callaghan Innovation's metal diaphragm pressure wave generator technology (DPWG). The metal diaphragms in a DPWG separate the clean cryocooler working gas from the oil lubricated reciprocating mechanism. DPWG technology has matured over the last 10 years to become a viable option for providing acoustic power to large pulse tube cryocoolers. The largest cryocooler consists of three in-line pulse tubes working in parallel on a 1000 cc swept volume DPWG. It has demonstrated 1280 W of refrigeration at 77 K, from 24 kW of input power and was subsequently incorporated into a liquefaction plant to produce liquid nitrogen for an industrial customer. The liquefier has now completed one year of operation, producing 11 liters of liquid per hour. Development of the pulse tube has continued with a single in-line pulse tube directly mounted to a 330 cc DPWG. The pulse tubes on the large cryocooler each produced 450 W of refrigeration at 77 K. Further optimization of the single unit has increased the cooling power to 500 W at 77 K, with no change in input power. This paper presents the experience obtained from running the large liquefier for a year in an industrial setting and the results of the optimization exercise on the smaller cryocooler.

INTRODUCTION

Callaghan Innovation and Fabrum Solutions have been developing cryocoolers based on metal diaphragm pressure wave generators (DPWG) for pulse tube[1–3] and Stirling [4] cryocoolers.

A range of industrially robust cryocoolers have been developed that are suited to cooling High Temperature Superconductor (HTS) applications such as transformers, power cables and fault current limiters, or for on-site production of industrial liquid nitrogen. The DPWG uses metal diaphragms to separate the pulse tube or Stirling cold-head's clean working gas from an ambient pressure, oil lubricated, motor-crank reciprocating mechanism. The result is an environmentally robust long-life cryocooler that is easily maintained.

The PTC1000 is the largest pulse tube refrigerator made to date and it has demonstrated 1280 W of refrigeration at 77 K from 24 kW of input power [2]. The PTC1000 consists of three in-line pulse

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tubes sharing the pressure wave from a single 1000 cc swept volume DPWG[5]. The pulse tubes' cold heat exchangers were fitted with condensers to allow liquefaction of nitrogen. The system produced an average 12.1 litres of nitrogen per hour during initial testing[3].

The liquefier has been installed and operated at a gas company in Christchurch, New Zealand. The gas company primarily supplies bottled gas, which is either imported or produced from its own air separation column, and liquid nitrogen to a small local market.

The development of the triple pulse tube cryocooler required development of a single pulse tube working on a 330 cc swept volume DPWG. The single pulse tube refrigerator, the PTC330, is a viable cryocooler in its own right and development of it has continued with results applicable to the large cryocooler. Areas for development were simplification of the pulse tube construction to reduce manufacturing cost, experimental optimization for increased refrigeration power and condenser design for efficiency.

A PTC1000 based liquefier incorporating the alpha-prototype 1000 cc DPWG was installed in July 2015 and ran for 11 months. The alpha-prototype DPWG was replaced with a production DPWG in June 2016 which, at the time of writing, is still in service. This paper presents the performance and experiences of running the liquefier on site and presents results from the single pulse tube's performance optimization.

THE LIQUEFIER SYSTEM

Figure 1 shows a schematic of the liquefier. The cryocooler's pressure wave generator (1) was powered by a standard 3 phase induction motor (2), which is controlled by a variable speed drive (3). A Nitrogen generator (4) supplied gas to the system. A solenoid valve (5) controlled by a pressure switch controlled the pressure in a buffer tank (6). Nitrogen gas was fed from the buffer tank to the cryocooler's condenser via gas line (7). The condensers were incorporated into the pulse tubes' cold heat exchangers inside the cryostat (8). Condensed nitrogen from each pulse tube was combined in the cryostat and drained via a vacuum insulated line (9) into the buffer Dewar (10). When the buffer Dewar became full, a solenoid valve (11) on the relief of the tank (12) to be filled was opened allowing pressure to drop and liquid to flow into the storage Dewar. An industrial PLC controller monitors the buffer Dewar level, controlled the output solenoid and the cryocooler motor (for example turning the cryocooler off when Dewars were full). Heat rejection for the cryocooler was achieved with a closed water circuit exchanging heat with the ambient air via a radiator.

THE INDUSTRIAL SITE

Figure 2 shows the liquefier installed in the main factory building. The industrial building is not insulated and has an iron roof and concrete walls. The liquefier was positioned close to a steel

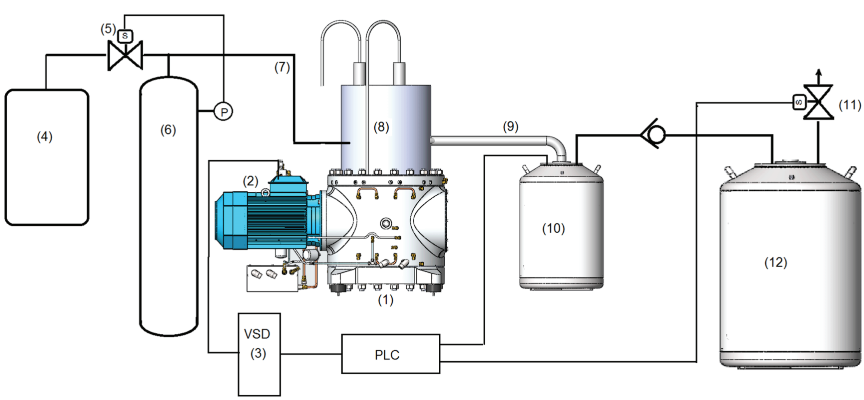

Figure 1. Schematic of the liquefier system.

Figure 2. The liquefier installed in the factory.

overhead door which could be opened on hot days to allow air to circulate and provides little insulation in cold weather.

The liquefier was installed in July, which is mid-winter in New Zealand. The winter temperatures in July had a maximum of 20 °C and minimum of -5 °C with an average daily maximum of 11 °C; contrasting to summer when the December maximum was 36 °C and minimum 2 °C with average daily maximum of 22 °C. The general machine and oil temperatures followed the ambient temperatures as would be expected from an air-cooled system. The general machine temperature was typically 15 degrees warmer than the ambient air in the factory and the oil temperature 30 degrees warmer than ambient.

DATA LOGGING

Running a machine in the field rather than in the development laboratory requires a degree of separation between operation and engineer. A data logging system was set up on the liquefier to allow the development team to monitor and record the liquefier's operation. The data logging system was purposely separate from the machine control. If a failure of the logging occurred, the machine control would continue to operate the liquefier in a safe manner.

The data logger measured machine parameters such as temperatures, motor power, gas and oil pressures, and Dewar level. The data logger hosted a web page and an FTP site on Callaghan Innovation's local area network via a cellular network router. Once the connection was made, the data logger could be accessed from the office network and allowed the development team to remotely view and control the data logger. A script running on a Linux computer was used to automatically upload the data from the data logger to a database file on the office network; where it could be analyzed by the development team. Most of the issues encountered during the field testing exercise were centered on getting the different components of the data logging system working smoothly. The system needed to automatically restart and send information in situations such as network connection loss or power-off by the customer. By the end of the 11 month trial we had encountered and accounted for most situations, so the monitoring was working reliably.

RESULTS

Figure 3 shows the running history of the cryocooler. Running time was 3338 hours with a duty cycle of 42%, over 30,000 liters of liquid nitrogen was produced for sale. There were 67 start-stop cycles with periods of running up to 271 hours at a time. One of the realities of an industrial site was a variable duty cycle driven by customer demand for the liquid nitrogen produced. This was caused by surplus liquid nitrogen production and shortages of Dewar capacity, where the empty Dewars would be at customers' premises. For the period from late August to the start of February, the liquefier produced significantly more liquid nitrogen than could be sold, so the liquefier was stopped for significant periods while waiting for Dewar capacity before the cryocooler was able to be restarted. At the beginning of February, a new order that required the full capacity of the liquefier was secured by the gas company and it was run full-time. By this time, the cryocooler liquefier had demonstrated that it was significantly cheaper to run than the gas company's air separation plant. Even so, there were short periods when the storage Dewars were full and the cryocooler was stopped.

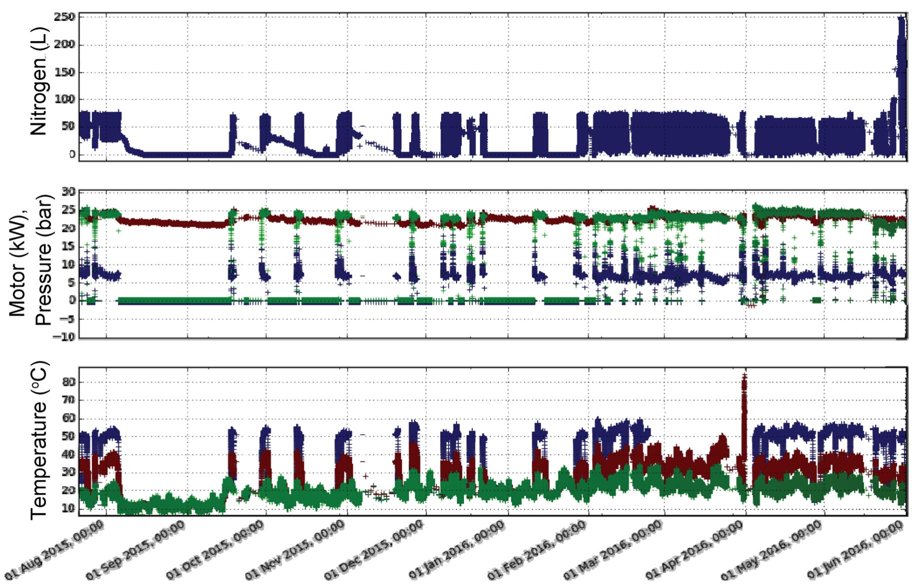

Figure 3: Running history of cryocooler over the 11 months of use. The top plot is the quantity of liquid in the buffer Dewar. The middle plot shows the oil pressure (blue), mean gas pressure (red) and motor power (green). The lower plot shows the oil temperature (blue), machine temperature (red) and ambient temperature (green).

Liquefaction Rates, Condenser Performance, Pulse Tube Performance

Figure 4 shows a typical production for two days of operation with the liquefaction rate approximately 11 liters per hour. The water temperature shows that the fans and radiators of the cooling circuit maintained the cooling water at approximately 4 degrees above the ambient temperature. The motor power shows a slight variation synchronized with the ambient temperature. The machine temperature affects the working gas pressure and therefore the acoustic power input.

The three pulse tubes consistently held temperatures within 4 degrees of each other. The thermal link between the pulse tubes had a conduction capacity of 0.5 W/K [3] which means that the pulse tube performances were very similar, transferring only 2 W between them.

The motor power input was steady at 24 kW when warmed up. The cooling system's circulation pump and radiator fans consumed 2.5 kW of electricity. The energy cost for the nitrogen liquefied, at a rate of 11 litres per hour was therefore 2.5 kWh/litre.

Liquefier System

Over the course of the year, optimizing the condensing and liquid handling system was carried out with many variations of the Dewar pressure, and control scenarios tried. There were combinations that produced stable liquefaction and others that could produce run-away freezing due to liquid build-up in the condenser. Run-away freezing of the nitrogen occurs when the liquid nitrogen film on the condensing surface becomes too thick, causing a temperature gradient through the liquid. As the film thickness increases, the temperature gradient increases, and the cold head temperature decreases, until the cold head reaches 64K and freezing occurs. The frozen layer then quickly thickens and blocks the condenser, at which point the cold head temperature plummets to its no-load temperature of approximately 40 K. Once the cryocooler was stopped and warmed up above the freezing temperature of 64 K, the liquid drained away and normal operation could be resumed.

Event

After initial bug fixing during installation and commissioning, the cryocooler settled down to steady operation. There was only one event in the 11 months of operation. On the 30th of March, a fitting started to leak cooling water into the cryostat. Cooling water filled the cryostat and the cooling

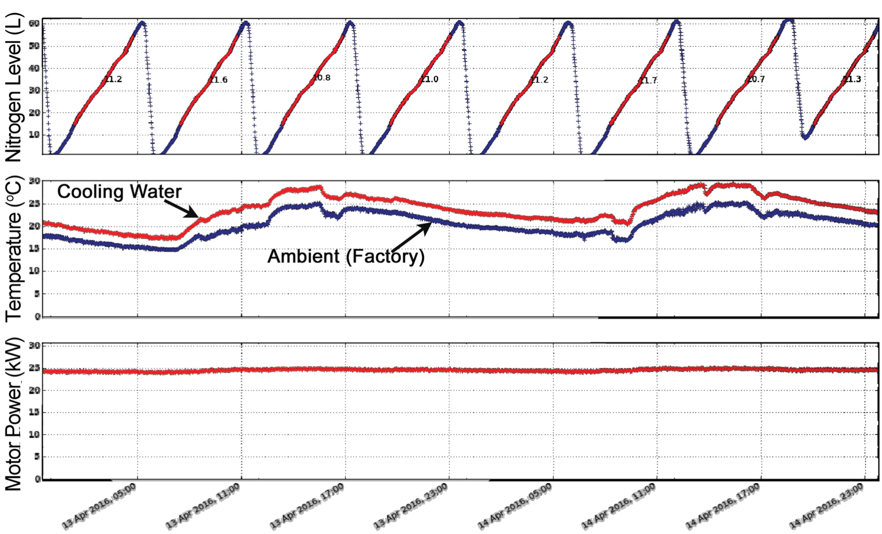

Figure 4. Two typical days of production. The top plot is the liquid nitrogen level in the buffer Dewar, with the average production rate for each filling cycle. The middle plot shows the ambient temperature in the factory (blue) and the cooling water temperature (red). The lower plot shows the motor power.

water reservoir eventually ran out. The loss of cooling water caused the temperature to rise (Figure 3 shows a temperature spike just before 1st of April) and the machine's safety interlocks shut it down.

The data logging and reporting back to base told the story as shown in Figure 5. The whole sequence took approximately 20 minutes. Firstly a small rise in condenser temperature at 07:48 indicated that the vacuum in the cryostat was degrading (when the water entered the cryostat), next the outlet water temperature became unstable when the water supply started getting low and produced an unsteady flow. The machine temperature started to rise and the sudden rise in the condenser temperature at 8:07 occurred when water reached the cold parts of the liquefier. Soon after, one of the safety switches was tripped and it stopped the machine. The pool of water in the cryostat protected the pulse tube aftercoolers from overheating. All the other machine signs such as gas pressure, pressure ratio, motor power, looked normal.

We were able to remotely diagnose the above scenario and made the decision to bring the cryocooler back to base. The cryocooler was removed from the liquefier on-site and returned to base on a Thursday, the water leak was repaired, cryostat cleaned out and the wet MLI replaced on the Friday. As a precaution, we replaced any sensitive parts that may have been affected by the temporary thermal load. The cryostat and gas spaces were vacuumed over weekend to remove left over moisture from the leak. It was refilled with helium, delivered, fitted into the cryocooler and back in service on Monday. The water fitting that caused the sequence of events has been removed from the production version to prevent the event from recurring.

PULSE TUBE DEVELOPMENTS ON PTC330

The testing and development of the single pulse tube cryocooler, the PTC330, was focused on confirming manufacturing improvements and management schemes for steady nitrogen condensation. The original pulse tube prototype was constructed with bolted joints between the regenerator, cold head and pulse tube to allow experimental optimization of the geometry. This design, whilst required for experimentation, is not a viable production solution. Once the regenerator proportions had been finalized, a design incorporating brazed joints was tested.

Another improvement feature was the pattern of the slots in the aftercooler and warm heat exchanger. The original design used radial slots with a pin filling the hole in the centre where the slots intersected, similar to the heat exchangers used by Ercolani et al [6]. In the original pulse tube the pin loosened over time. An alternative heat exchanger pattern was devised which allowed cutting of the slots without a central hole, thus eliminating the pin.

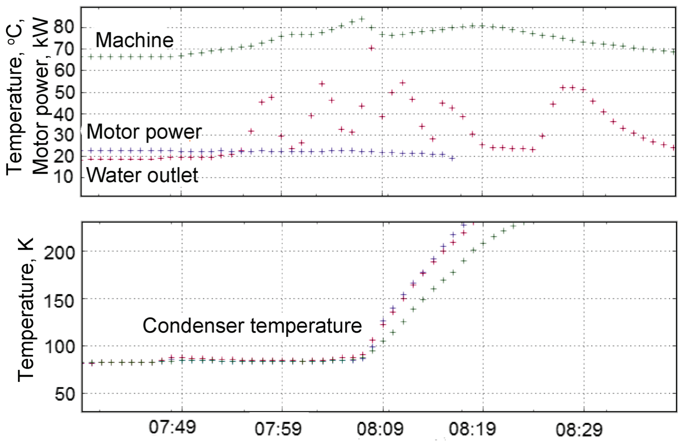

Figure 5. Data logger record of event showing (from top to bottom at start of record): machine temperature monitor (green), motor power (blue), water outlet temperature (red) and on the lower plot the three pulse tube condenser temperatures.

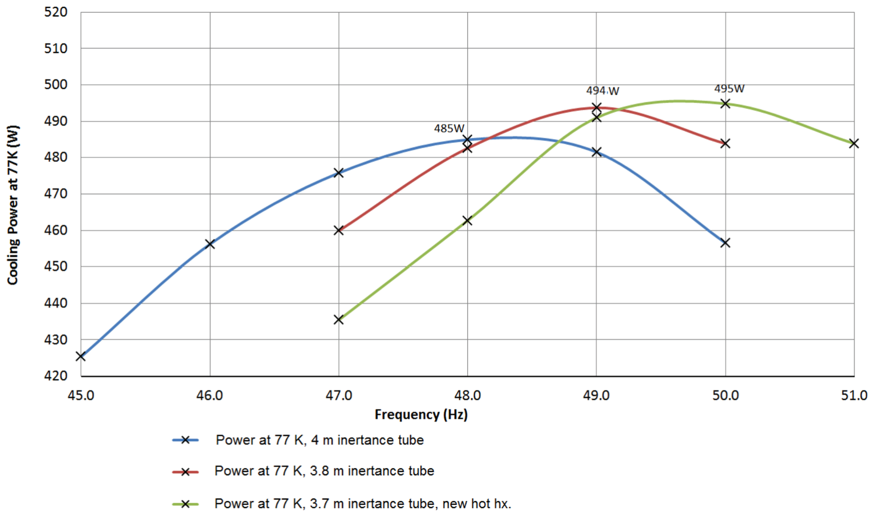

Figure 6. Frequency sweeps for the production design PTC330's cooling power at 77 K; tuning for 50 Hz running and the new hot heat exchanger design.

Figure 6 shows that tuning of the inertance tube length and incorporation of the new hot heat exchanger design has increased the operating frequency from 48 Hz to 50 Hz, with an increase in cooling at 77 K from 485 W to 495 W. The ability to tune for a given operating frequency with minimal effect on the refrigeration power or efficiency is a function of the non-resonant DPWG. It is very useful if the larger system that the cryocooler is installed into has a particular operating frequency to avoid.

The PTC330 has been configured as a liquefier and was installed for endurance testing at the gas company alongside the PTC1000. It has been producing liquid nitrogen at a rate of 4.7 liters per hour.

CONCLUSIONS

Fabrum Solutions and Callaghan Innovation now have an excellent endurance test site for cryocoolers. The gas company provides an industrial environment, real duty cycles, and a commercially viable use for the liquid nitrogen produced. The close location of the site to the development team aids monitoring but there is enough separation to provide the operation of the liquefier by the gas company and therefore provides a real-environment test.

The DPWG has proved to be a reliable pressure wave generator for the pulse tubes and ran for 3338 hours over the 11 months of testing. It ran in a dusty, un-insulated, environment throughout a winter and a summer, with large daily temperature swings. This is seen as an exceptional result as the DPWG used in the test was the first prototype of the 1000 cc DPWG. The DPWG technology has improved considerably since its design and construction and the alpha-prototype DPWG in the liquefier has now been replaced with a production version. The next step for the alpha-prototype DPWG is to strip and inspect so that learnings from its running can be incorporated into future machines.

The pulse tubes produced consistent performance liquefying at approximately 11 l/hr. Condenser design and management are continuing to be developed. The radiator based cooling system has proven itself over a wide temperature range.

Performance improvements and production refinements on the PTC330, single pulse tube cryocooler have resulted in a liquefier producing 4.7 liters per hour.

The next steps are to continue running the PTC1000 liquefier alongside the PTC330 based liquefier at the gas company. The reduced cost of liquid nitrogen production, made possible by the pulse tube based liquefiers, has allowed the gas company to secure more customers and has increased liquid nitrogen demand. These two liquefiers will be joined by three more in four months' time, making a total of five units producing commercial liquid nitrogen.

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