Commercialisation of Pulse Tube cryocoolers to produce 330 W and 1000 W at 77 K for liquefaction

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Abstract. Fabrum Solutions in collaboration with Callaghan Innovation has been developing large pulse tube cryocoolers based on Callaghan Innovation’s diaphragm pressure wave generators (DPWG). The pulse tube’s lack of moving parts in combination with the DPWG’s metal diaphragms produces a cost-effective, long life and robust cryocooler. The DPWG has had 10 years of development, resulting in a series of DPWGs ranging in input powers from 0.5 kW to 30 kW that have been coupled to a variety of in-line and coaxial pulse tubes. Two DPWGs have had in excess of 7000 hours running to date. The PTC330 cryocooler is based on a new 330 cc DPWG and has produced 480 W of cooling at 77 K during testing. The PTC1000 combines three such pulse tubes on a single 1000 cc DPWG to produce 1270 W at 77 K. This paper details the development of the PTC330 and PTC1000 cryocoolers from initial lab prototypes through to commercial products, integrated into liquefiers and ready for use in applications such as: Nitrogen liquefaction, re-liquefaction of boil-off from storage tanks, or cooling of cryostats for High Temperature Superconductor applications.

1. Introduction
Callaghan Innovation has been developing cryocoolers based on metal diaphragm pressure wave generators (DPWG) for pulse tube and Stirling cryocoolers since 2005. The objective of the work is to produce an industrially robust cryocooler for High Temperature Superconductor (HTS) applications and gas liquefaction. The DPWG is a practical alternative to crank or linear-motor driven pressure wave generators. The DPWG has the simplicity and low cost of a lubricated crank system with the diaphragms providing a non-rubbing hermetic seal to maintain a clean cryocooler working gas. To date, 15 pressure wave generators have been made with swept volumes from 20 cc to 1000 cc [1]–[3]. These have all been coupled to pulse tube[4]–[7] or Stirling[8], [9] cold heads. Two of the DPWGs have each achieved over 7000 hours of operation.

Two years ago, Fabrum Solutions became Callaghan Innovation’s commercialization partner. Fabrum Solutions identified market opportunities for cryocoolers with approximately 330 W and 1000 W at 77 K, primarily for HTS cooling and liquefaction of nitrogen. Since then development has focused on producing commercially ready pulse tube cryocoolers to meet these targets. Fabrum Solutions is now able to offer to the market industrially rugged cryocoolers with 450 W and 1250 W of cooling at 77 K.
Cryogenic cooling of HTS systems has a unique set of requirements that were identified by the US Department of Energy (DOE) roadmap and published in 2001 [10]. The DOE roadmap identified the need for cryocoolers with 100-1000 W at 65-80 K with an efficiency of 30% of Carnot, capital cost of $25 per watt of cooling at 77 K and 99.8% availability; goals that are ambitious for technology today. Most importantly for today’s HTS demonstration projects, the cryocoolers must meet the cooling power (the ability to do the task) and availability (the ability to keep doing the task) goals. Additionally, such a cooling system must be able to function with a variable cooling load. That is, the cooling system needs to be efficient when the HTS application is lightly loaded, provide continuous cooling under full load and be able to provide significantly more cooling for a short time under overload or fault conditions. These requirements can be met by the use of multiple cryocoolers working with a buffer tank of liquid nitrogen. The buffer tank can meet the high loads from faults or transients, and the multiple cryocoolers can be used for load matching and redundancy; enabling a cryocooler to be taken out of service without interrupting the cooling system. Such a system was proposed for the Albany HTS cable project which was cooled by a bulk tank and 2 x 4 kW of Stirling cryocoolers [11]. The system demonstrated resilience in the event of a sudden cryocooler stoppage, without disruption to the cable temperature. The Tokyo Electric Power Company HTS cable in Japan is similar with 6 cryocoolers [12].

Current estimates for transformers and cables suggest that cooling systems with capacities of 5 to 10 kW at around 70 K will be required. The ideal cryocooler unit size for these systems is 1 to 2 kW. For these reasons Callaghan Innovation developed the 1000 cc DPWG [3] as a key enabler for industrial cryocoolers of over 1000 W at 77 K capacity. The DPWG has been designed for manufacture in small batches, therefore not requiring high production numbers to reduce cost.

A nitrogen liquefier based on the DPWG has other uses, such as the production of liquid nitrogen for industry in remote areas. Industrial processes, like laser cutting or food packaging, use significant quantities of nitrogen gas, which is often supplied and stored in liquid form. Liquid nitrogen delivery is economical where the supply chain is good, but when the transport time from the liquefaction plant to use is days, or weeks, then the logistics of transporting a cryogen increases the price of liquid nitrogen to the point where on-site production becomes an economical alternative.

This paper presents the development of two commercial pulse tube cryocoolers, the PTC330 and PTC1000, for industrial liquid nitrogen production and cooling HTS applications.

**Figure 1.** Cooling power and Carnot efficiency for the PTC330 pulse tube on the 330 cc DPWG.
2. PTC1000 configuration
The PTC1000 cryocooler consists of three in-line pulse tubes that share the compression space of a 1000 cc swept volume DPWG. The ‘triple in-line pulse tubes on a single DPWG’ configuration was chosen over co-axial or single pulse tube alternatives for three reasons. Firstly a single pulse tube was ruled out because the large hydraulic diameter of the pulse tube increases the risk of 3D flows, causing instability and power loss. Secondly, the co-axial configuration turns the gas 180° in the cold heat exchanger, which again increases the risk of 3D flows in the pulse tube. And thirdly our pulse tube designers at Absolut System, have experience with similar size in-line pulse tubes coupled to DPWG’s, producing 600 W at 120 K pulse tubes for a cryogenic CO$_2$ scrubber [13]. Additional benefits from multiple pulse tubes include cost savings from higher production numbers, and a single pulse tube on a 330 cc DPWG, the PTC330, is a useful cryocooler in its own right.

Pulse tubes perform best with the cold heat exchanger below the pulse tube to suppress gravity-induced 3D flows from the large temperature-induced density gradient inside the pulse tube. Therefore, an in-line pulse tube is best mounted on top of its DPWG. Top-mounting of a pulse tube has additional benefits as it positions the cold head high, allowing liquid to drain from the condenser into a Dewar whilst keeping the heavy DPWG low.

3. The PTC330 cryocooler development
The PTC330 in-line pulse tube was designed for a 330 cc swept volume DPWG. Details of the pulse tube development are presented in another paper at this conference.

A new DPWG, with 330 cc swept volume, was designed for testing the PTC330 pulse tube. The design of the 330 cc DPWG was based on the successful 90 cc DPWG [7], which had counter-rotating shafts and a hydraulic lifter to move the diaphragms. Features from the 1000 cc DPWG prototype [3] were incorporated into the 330 cc design such as: improved lifter details and water cooling, and an external oil sump. The result was a production-ready DPWG with 330 cc of swept volume, capable of producing 7 kW of PV power from ~12 kW of motor input power. The 1000 cc DPWG production design was then updated to be consistent with the new 330 cc design.

Figure 2. The PTC330 cryocooler in a re-liquefier for condensing boil-off from storage Dewars.
Three 330 cc DPWGs were manufactured as the first production batch: one for Callaghan Innovation’s test laboratory, one for endurance testing and one for demonstration.

The laboratory DPWG was used to develop the single PT330 pulse tube, which immediately exceeded its target of 330 W at 77 K. Experimental optimization of the pulse tube, regenerator and inertia tube lengths produced 480 W of refrigeration at 77 K from 7.3 kW of PV power and 12.0 kW of motor power. Figure 1 shows the PT330 pulse tube’s cooling curve. Of note is that the cooling power increases with temperature; approximately 600 W of heat lift is available at 90 K (oxygen liquefaction) and 900 W at 120 K (methane liquefaction). The cryocooler weighed 450 kg.

The endurance test unit was fitted with a pulse tube and condenser, coupled to a Dewar, and a control system to produce the stand-alone liquefier shown in Figure 2. It has been in service from January 2015 at Christchurch gas firm, Southern Gas Services, where it has been liquefying nitrogen gas from a pressure-swing nitrogen generator. The unit is still in active service.

The third unit has been coupled to a pulse tube for display and trial by potential customers. This unit was on display at the Fabrum Solutions stand at this meeting.

### 4. The 1000 W cryocooler

Three identical PTC330 pulse tubes were manufactured for mounting on a single 1000 cc DPWG[3] to create the PTC1000 cryocooler. The area of the DPWG’s compression diaphragm was divided into three equal segments with the pulse tubes positioned at the centroids of their respective area segments. A triskelion shaped copper plate connected the cold heat exchangers of the three pulse tubes to aid temperature balancing. The triskelion shape limited bending stresses to allowable levels while the cold copper sections contracted and the pitch circle of the pulse tubes remained set by the warm DPWG, all whilst minimising the conduction length.

The single PTC330 cryocooler used the DPWG’s gas spring as a reservoir, thus equalising the average gas pressure on each side of the DPWG. Connecting three inertia tubes into a single reservoir on the 1000 cc DPWG’s produces circular flow paths between the pulse tubes, which could cause DC flows and instability leading to a loss in performance. To ensure that circular flows did not occur, each pulse tube was provided with its own reservoir. A capillary line was connected between the gas spring and one of the reservoirs to equalise the average gas pressure across the DPWG. Each pulse tube was individually tested on the 330 cc DPWG before mounting on the large cryocooler. The cooling curves of the individual pulse tubes are shown on Figure 3. Pulse tube A achieved 400 W at 77 K, with a no-load temperature of 40 K. Pulse tubes B and C achieved identical performances with 450 W at 77 K, which suggests slightly different tuning. Combining the results, the PT1000 would be expected to produce 1300 W at 77 K from 21 kW of PV power and weighs 1000 kg.

![Figure 3. Cooling power curves for the three pulse tubes, denoted A,B and C, tested individually on the 330 cc DPWG prior to fitting to the 1000 cc DPWG.](image-url)
Figure 4 shows the PTC1000 cryocooler during testing at Callaghan Innovation. The refrigeration performance of the PTC1000 was tested using three heater sets in parallel, provided with the same voltage from a single power supply. A PID controller was used to adjust the heater power to keep the temperature transducer on pulse tube A at a set temperature.

The cooling curve and efficiency for the PTC1000 is shown in Figure 5. Cooling power at 77 K was measured to be 1270 W from 18 kW of acoustic power and 24 kW of motor power, which exceeds the original target of 1000 W at 77K. The cooling power is close to the 1300 W sum of the individual pulse tube powers. However, the efficiency of the PTC1000 was higher than the individual PT330’s, with an over-all COP at 77 K of 5.3% corresponding to a Carnot efficiency of 15%. Importantly for HTS applications, the cryocooler provides over 1000 W at 70 K, 300 W at 50 K and has a no-load temperature of 43 K.

Maximum refrigeration power was achieved with the variable speed drive set to 47 Hz. The frequency response of the PTC1000 was similar to the PTC330. Further fine tuning of the inertance tubes could move the peak performance to 50 Hz for on-line running, although optimal efficiency for the whole system is likely to be at a lower frequency as the mechanical efficiency of the DPWG improves with lower frequencies. The DPWG is not resonant, so it is capable of efficient running at a range of speeds and can be readily changed with a standard industrial variable speed drive to match the pulse tube performance exactly. The use of a variable speed drive to achieve the slower speed, especially in areas with 60 Hz supply, adds benefits to the whole system when compared to the alternatives of soft-starters, overload, contact breakers, timers and efficiency losses from operating at sub-optimal speeds.

![Figure 4](image)

**Figure 4.** The PTC1000 pulse tube during testing at Callaghan Innovation.
5. Stability and temperature difference between pulse tubes

A 24 hour stability test was performed on the PTC1000 while recording the individual pulse tube temperatures and heater power. The PID controller was used to adjust the power into the heaters to keep pulse tube B at a constant 77 K. Figure 6 shows the stability run temperatures and heater power. Starting from the no-load temperature, the PID controller took approximately two hours to stabilize. It held pulse tube B to within 0.2 K of the target 77 K. The temperatures of all three pulse tubes remained steady, as did the refrigeration power, which stayed within 0.5 W of 1250 W. No large scale fluctuations in temperature or input power were observed.

Throughout the testing, pulse tube C was consistently 1 K lower in temperature than pulse tube B, with pulse tube A 0.3 K below pulse tube B. This is unlikely to be a measurement issue as each pulse tube had two temperature transducers, which consistently agreed with each other. It is also unlikely to be caused by differences in heater resistances as the temperature differences were observed during cool-down, with the heaters off. The most likely cause is a slight difference in tuning between the pulse tubes, possibly due to the shape of pulse tube C’s inerternce tube which, whilst the same length as A and B, was slightly different to accommodate its position relative to its reservoir.
6. Conclusion
Fabrum Solutions now has two cryocoolers ready for commercial use. The first cryocooler, denoted the PTC330, is a single in-line pulse tube running on a 330 cc swept volume DPWG that has produced 480 W of cooling at 77 K. The second cryocooler, denoted the PTC1000, combines three in-line pulse tubes on a single 1000 cc DPWG and is capable of 1250 W of refrigeration at 77 K with a Carnot efficiency of 15%. The pulse tube’s lack of moving parts combined with the DPWG’s ruggedness and mechanical simplicity have resulted in a cryocooler that is ideally suited to liquefaction of gases in industrial environments and is particularly well suited to applications such as refrigeration for large HTS transformers and cables.

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