330 W Cryocooler Developments and Testing

N Emery, A Caughley, M Nation, A Kimber, N Allpress, H Reynolds, C Boyle, J Meier and J Tanchon

1Callaghan Innovation, Christchurch, New Zealand
2Fabrum Solutions, Christchurch, New Zealand
3Absolut System SAS, Meylan, France

E-mail: nick.emery@callaghaninnovation.govt.nz

Abstract. Fabrum Solutions in association with Callaghan Innovation and Absolut System has developed a 330 W pulse tube cryocooler based on Callaghan Innovation's novel diaphragm pressure wave generators (DPWG). A cost-effective, long life and robust cryocooler has been achieved due to the pulse tube's lack of moving parts and the DPWG's metal diaphragms separating the working gas from the oil lubricated drive mechanism. A 330 cc DPWG was designed and manufactured to run with an inline pulse tube. Absolut System carried out the pulse tube design; manufacture was by Fabrum Solutions, with integration and testing by Callaghan Innovation. The 330 W pulse tubes were run as cryocoolers mounted to 330 cc DPWG's. 480 W of cooling power at 77 K was achieved (target was 330 W at 77 K) from 7kW PV power and 12 kW of electrical input power. An endurance cryocooler was assembled with the left over parts from the optimization exercise. The endurance cryocooler was assembled to run as a liquefier. Calculation showed that 1 litre per hour of liquid nitrogen production was possible from 91 W of cooling power at 83 K. 1 litre per hour of liquid nitrogen was successfully produced for every 100 W of cooling power at 83 K, in a commercial application. Three more 330 W pulse tubes have been mounted to a single 1000 cc DPWG to produce > 1 kW of cooling power at 77 K. The commercialisation of the 1000 W cryocooler is the topic of another paper presented at this conference. Details of the design, development, testing and integration of the 330 W cryocooler are presented in this paper.

Introduction

It has been 10 years since the first diaphragm pressure wave generator (DPWG) prototype was produced at Callaghan Innovation. In total 15 DPWG's have been built with various swept volumes ranging from 20 to 1000 cc[1]. Callaghan Innovation has also successfully produced several large pulse tubes, both in-line and co-axial configuration, of between 10 and 110 W at 77 K [2][3]. A 110 W pulse tube cryocooler was integrated into a liquefaction plant to allow turn-key liquefaction of liquid nitrogen using a pressure swing adsorption (PSA) technology to provide the nitrogen gas.

Fabrum Solutions have taken the lead in commercialising the DPWG technology, having taken over from HTS-110 two years ago. Fabrum Solutions is New Zealand based, has a strong manufacturing background, an international reputation in composite cryostats and is proving to be an ideal partner for Callaghan Innovation. A serious drive to get the cryocoolers into useful applications has focused the development and accelerated the commercialisation of the technology.

Field testing to date has been based around liquefaction of nitrogen. Gas liquefaction in general (nitrogen, oxygen, natural gas, etc) and High Temperature Superconducting (HTS) cooling have been...
identified as ideal applications for the technology. The aforementioned applications have the same theme in common: the need for industrial, long-life and reliable cryogenic cooling. The DPWG coupled with pulse tube technology matches these requirements. A clean working gas space, separated from the conventional oil lubricated crank driven drive mechanism by metal diaphragms, with no moving parts in the cold space are the inherent benefits of the cryocooler technology.

Callaghan Innovation has successfully developed co-axial pulse tubes for use with DPWG’s[2], working with Absolut System on the design of a 100 W co-axial pulse tube[3]. Absolut System has also successfully developed 3x 280 W @ 77 K in-line pulse tubes on three 240 cc DPWG’s[4].

**Diaphragm Pressure Wave Generators:**
A new industrial 330 cc metal diaphragm pressure wave generator (DPWG) was designed based on the previous 90 cc DPWG [1]. Three 330 cc DPWG’s were manufactured: a development machine, an endurance test machine and a field trial demonstration unit. The units were driven by a standard industrial 11 kW 3-phase motor, with counter rotating shafts driving pistons to run a hydraulic drive, to reduce the stroke and increase the force on the diaphragms. Two opposing diaphragms were used to reduce the load on the crankshaft bearings, one to drive compression and the other into a gas spring. The 330 cc DPWG took another step forward for production - the oil and cooling system circuits were integrated into the casting and an off the shelf external reservoir was used. Oil flow back to the reservoir was improved on the 330 cc DPWG. The DPWG can be run at a range of operating frequencies, as the system is not required to resonate, making the resonant tuning of a pulse tube a straightforward process.

**Pulse tubes:**
Absolut System designed a nominal 330 W inline pulse tube to be close-coupled to the 330 cc DPWG’s and three of the pulse tubes were mounted on a 1000 cc PWG. The inline pulse tubes were designed to run at around 50 Hz operating frequency and provide 330 W at 77 K.

The pulse tubes were manufactured by Fabrum Solutions, along with composite cryostats to allow vacuum insulation of the cold-head. The pulse tube components went through a cleaning cycle at Callaghan Innovation that included chemical cleaning with acetone and ethanol followed by convection and vacuum baking to ensure outgassing within the pulse tube was minimised.

The pulse tubes were then assembled in a clean room at Callaghan Innovation, before testing. Assembly was to Absolut System’s specifications with tuning planned for inertance tube length, pulse tube length and regenerator length. Inertance tube, pulse tube and regenerator tube lengths were changed as well as heat exchangers, regenerator mesh type and density. The inertance tube was initially run into a reservoir (10 L gas bottle), but was subsequently successfully trialled running it into the DPWG gas spring, which reduced part count and made a tidier, more compact system. The regenerator was constructed from wire mesh sheet that was cut to produce a stack of mesh disks. The heat exchangers were wire-cut to allow efficient transfer of heat to and from the copper and aluminium materials, and water cooling was used on the warm heat exchanger and after-cooler heat exchanger to remove heat. Multi-layer Insulation (MLI) and vacuum were used to insulate the cold-head from thermal losses due to convection and radiation.

**Cryocooler Performance Testing**
Development of the 330 W cryocooler took place at Callaghan Innovation. Figure 1 shows the cryocooler running a copper inertance tube into a helium gas bottle reservoir. Copper was used for the inertance tubes in the tuning phase of the development due to its ease of bending and low cost. Testing showed a 20 W loss in performance by running the inertance tube into the gas spring, but was outweighed by the complexity of running the inertance tube into the reservoir bottle, whilst still needing to equalize the pressure between the gas spring and compression space of the pulse tube. A stainless steel inertance tube was formed into shape once the final inertance tube length was determined through testing. A water chiller was used to cool the system for the lab based testing,
which was subsequently replaced by a Fabrum Solutions supplied air to water cooling system when
the unit was setup to run as a nitrogen liquefier.

Resistive heaters were installed in the cold heat-exchanger for power to be transferred to the pulse
tube. A silicon diode thermometer was used to measure the cold-head temperature. PID control of the
power fed to the heaters allowed simple power vs. temperature performance to be generated. An
automated testing algorithm allowed testing to be conducted throughout the night un-manned to help
speed up development.

![Figure 1. 330 W Cryocooler at the Callaghan Innovation Laboratory](image)

**Performance Testing Results**
The first run up of the 330 W pulse tube produced 312 W at 77 K, which was very close to the target
of 330 W at 77 K. The result gave great confidence, as the expectation was that tuning the pulse tube
would exceed the target quickly. Inertance tube optimisation resulted in an easily achieved increase in
performance to 387 W at 77 K. Moreover, tuning the inertance tube allowed the optimum
performance to be achieved at the New Zealand grid frequency of 50 Hz. The significance of tuning
to grid frequency is that the cryocooler can be run on-line. Alternatively a variable speed drive (VSD)
can be used in 60 Hz grids or for fine tuning of speed for optimal efficiency.

Figure 2 shows the result of pulse tube and regenerator length changes and heat exchanger
development to reduce manufacturing cost, which had an extra benefit of a further increase in
performance. The cryocooler achieved 480 W at 77 K from 7 kW of PV power and 12 kW of motor
Moreover, 600 W at 90 K (liquid oxygen temperature) and 850 W at 115 K (liquid methane temperature) were also achieved.

![Cooling power and Carnot Efficiency](image)

**Figure 2.** 330 W cryocooler performance

### Liquefaction of Nitrogen

A pulse tube for an endurance machine was assembled out of the parts left over from the optimisation exercise. A lower cooling power was expected, which was acceptable as the aim was to prove endurance. A nitrogen liquefier was constructed using the endurance cryocooler.

A 2-stage liquid nitrogen condenser was designed to allow nitrogen gas, from boil off or PSA (or a combination of both), to be condensed on the pulse tube’s cold-head and transferred to a Dewar. The first stage allowed the nitrogen gas to be pre-cooled by directing it around the cold-head. The second stage was an open chamber that provided surface area for the pre-cooled nitrogen gas to be liquefied. The liquid nitrogen then drained under gravity into a 90 kPa storage Dewar. Losses were minimised in the transfer due to the vacuum jacketed line, cryostat and MLI that covered the cold-head and condenser assembly. The liquefier Dewar was placed on scales and the rate of increase of liquid nitrogen mass was used to confirm the calibration of the Dewar nitrogen level sensor.

The liquefier unit included an electrical box to house a soft starter for the motor and data acquisition & controls, a cooling pump, radiator and fan, new off the shelf oil reservoir with revised plumbing and a new frame to mount all the components on. Nitrogen gas bottles were used to provide the gas supply for initial testing of the liquefaction system at the Callaghan Innovation Laboratory, before the unit was released for field testing.
Field testing of the Nitrogen Liquefier

The liquefier unit, using the endurance cryocooler, was run at Southern Gas Services (SGS) in New Zealand. Pressure Swing Adsorption (PSA) was used to provide pressure controlled nitrogen gas to the liquefier. 3 phase power was provided for the motor & cooling pump and single phase for the Data Acquisition and vacuum pump. A working Dewar was used to accumulate the liquid nitrogen from the cryocooler, which was then transferred to a storage Dewar when the working Dewar was full.

An Omron model ZR-RX45 data acquisition system was used to capture 20 Channels of data including liquid nitrogen level, and various temperatures and pressures. The transfer of liquid nitrogen was automated using the nitrogen level sensor and venting system to lower the pressure in the receiving Dewar. The data acquisition transmitted data to a server on the Callaghan Innovation network via modem, with automated post-processing for ease of analysis. A webpage was generated by the device for real-time viewing of the important running parameters, and also allowed for remote control of the system such as stopping the cryocooler and draining the Dewar.

The unit successfully completed 1000 hours of running before returning to Callaghan Innovation for disassembly to inspect components for wear. The original liquefier had the nitrogen gas inlet in the liquefier Dewar, with a vacuum jacketed transfer line to feed the cryocooler with gas. The gas inlet was moved to run directly into the condenser on the cold-head, to remove the vacuum jacketed transfer line. The liquefier was subsequently reinstated at SGS and is, at the time of writing this paper, running an endurance test with the nitrogen being sold to Fabrum Solution’s customers. Calculation showed that for every litre per hour of liquid nitrogen production, 91 W of cooling power at 83 K was required. The calculation was based on 2 Bar absolute pressure tabulated values for the nitrogen enthalpy change from 300 to 83 K and the density of the liquid at 83 K [5]. Testing showed that for every 100 W of cooling power at 83 K, 1 litre per hour was produced, giving confidence in the condensing circuit design.

Figure 3 shows the nitrogen liquefier, including the 330 cc PWG, 330 W pulse tube, a 120 L 13 PSI Dewar and integrated air to water cooling system, all integrated on a single frame. Some of the advantages of the liquefier are: it can be run without a refrigerated cooling system and it uses the industrial DPWG to provide a clean working gas to the pulse tube cold-head, which has no moving parts to wear out. Maintenance of the cryocooler is limited to annual oil changes only, since the working gas is separated from the lubrication and motor windings. A display cryocooler is on the Fabrum Solutions stand at this conference.

Figure 3. Nitrogen liquefier operating at Southern Gas Services
Conclusion
The DPWG technology coupled to an in-line pulse tube has now evolved into a useful commercial product. The combination of Fabrum Solutions, Callaghan Innovation and Absolut System has produced an exceptional DPWG and pulse tube cryocooler that has achieved 480 W at 77 K from 7 kW PV and 12 kW motor power. The benefits to using the diaphragm technology are: oil lubricated PWG working mechanism, clean working gas and no moving parts in the cold space. Moreover, the cryocooler can be cooled by a non-refrigerated cooling system, further reducing complexity and both maintenance and capital costs. An endurance cryocooler was assembled from the left over parts from the optimisation exercise. A calculation showed that 91 W of cooling power @ 83 K was required to liquefy 1 litre of nitrogen per hour. The endurance cryocooler based nitrogen liquefier produced 1 litre per hour of liquid nitrogen for every 100 W of cooling power that the cryocooler delivered in its commercial application. The DPWG has been successfully up-scaled from 330 cc to 1000 cc to run three of the nominal 330 W pulse tubes. The 1000 W commercialisation is a topic of another paper being presented at this conference.

Acknowledgements
The authors acknowledge Callaghan Innovation in New Zealand for their support of this work, New Zealand’s MBIE for funding, Absolut System for the pulse tube design and Fabrum Solutions Ltd for manufacturing and commercializing the technology.

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