ABSOLUT
SYSTEM
INNOVATIVE CRYOGENIC SOLUTIONS
https://www.absolut-system.com
Article

Coaxial Pulse Tube Development

N. Emery[1], A. Caughley[1], N. Glasson[1], J. Meier[1], M. Nation[1], J. Tanchon[2], T. Trollier[2], A. Ravex[2]

[1]Industrial Research Ltd, Christchurch, NZ
[2]Absolut System SAS, Meylan, France

ABSTRACT

Industrial Research Ltd (IRL) previously developed a single-stage, coaxial, pulse tube for use with their 60 cc swept volume metal diaphragm pressure wave generator (PWG): 85 W of cooling power @ 80 K was achieved. This paper describes the development and testing of a larger cryocooler designed and built for small scale liquefaction. The pulse tube was based on a similar coaxial design to its predecessor, but was up-scaled by 50 % and close coupled to a 50% higher displacement 90 cc swept volume metallic-diaphragm PWG. Sage simulation software was used to model the pulse tube and predicted 120 W of cooling power @ 80 K. A prototype was designed and constructed. Experimental optimization resulted in 120 W of cooling power @ 80 K, with an electrical input of 3.1 kW. The pulse tube operated at 50 Hz, with average helium working gas pressure of 2.5 MPa. Details of the development, experimental results and correlations to the Sage model are discussed.

INTRODUCTION

IRL has developed a metal diaphragm pressure wave generator (PWG)[1] to deliver an industrial solution to providing a clean pressure wave to a coldhead. Pulse tube technology is developed to provide the expansion, and therefore the coldhead, phase of the cryocooler. Two previous inline pulse tubes[2,3] have been designed and run on 20 cc and 60 cc swept volume PWG's respectively. The single-stage inline pulse tube on the 60 cc PWG achieved 45 W of cooling power at 77 K, with 19.5 % of Carnot efficiency (based on PV input power). IRL's first attempt at a coaxial pulse tube expander close coupled to the 60 cc PWG produced 85 W of cooling power @ 80 K[4]. A beta version of the coaxial design was designed with a 50 % increase in capacity over the previous version. A 90 cc PWG was made to drive the pulse tube, which was designed to liquefy a nitrogen gas mix with a target refrigeration power of 100 W @ 77 K; hence it was named the PT100 Beta to indicate the nominal/design power at 77 K, and that it was a second generation design. The design and development of the PT100 Beta is described in this paper and was carried out in collaboration with Absolut System[5]. Three production field trial units based on the PT100 with 90 cc PWG are being manufactured at the time of writing this paper.

DESIGN AND MANUFACTURE

The specification for the cryocooler is listed in Table 1. Sage[6], an industry standard one-dimensional frequency domain modeler developed for Stirling and pulse tube systems, was used

Cryocoolers 17, edited by S.D. Miller and R.G. Ross, Jr.
©International Cryocooler Conference, Inc., Boulder, CO, 2012

Table 1. Cryocooler Specification

Parameter	*Specification*
Cold Temperature	77 K
Cooling load	>100 W
Heat rejection Temperature	300 K
Frequency	50 Hz
Mean working gas pressure	2.5 MPa
PWG swept volume	90 cc
PV Power	approx 1.5 kW

to model the pulse tube. The design started with the previous coaxial coldhead in Sage, and was modified to include a 90 cc swept volume PWG. The pulse tube dimensions were then changed to reflect the 50% greater volumetric capacity of PWG, with the assumption that a power increase of 50% would ensue. The regenerator cross-sectional area and length were increased, along with pulse tube volume and heat exchangers. Sage was then used to optimize the geometry for the best efficiency at 77 K. The Sage model geometry was created in CAD and the design was refined to enable manufacture. A two piece coldhead was replaced with a single piece design.

An indium o-ring was used to seal the cold head to the regenerator tube, allowing for a modular design and later experimental optimization, and a Viton O-ring was used to seal the regenerator to the aftercooler. Electron discharge machining (EDM) was employed on the heat exchangers to produce narrow flow channels and ensure accurate fits were maintained. Figure 1 shows the design of the coaxial pulse tube. Figure 2 shows the completed cryocooler. A description of the design of the main components proceeds.

Aftercooler Heat Exchanger

The aftercooler has been designed to extract heat from the working gas of the cryocooler by way of an internally finned heat exchanger integral with the PWG's aluminum compression plate. The design connects the aftercooler directly with the PWG compression space to minimize dead volume. The heat is removed by pumping coolant through water-cooling channels drilled into the PWG compression plate. The cooling water temperature for the tests was 290 K.

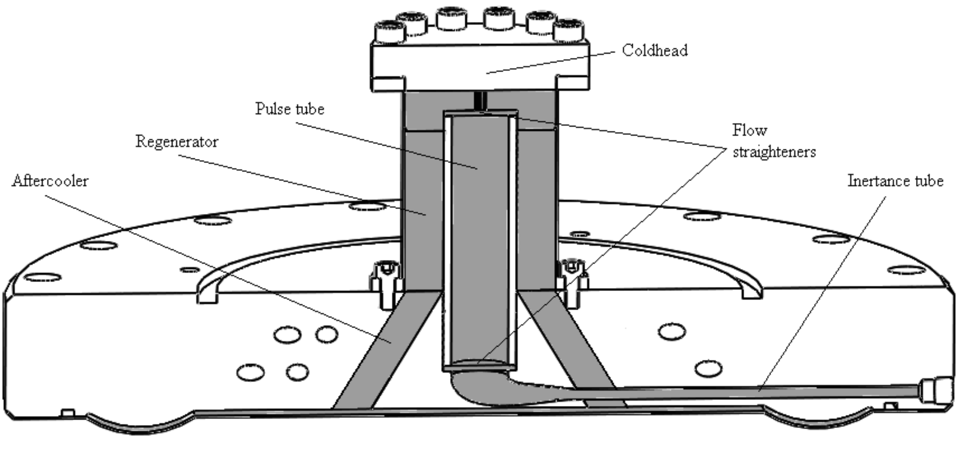

Figure 1. Cross-section of the PT100 Beta pulse tube

Figure 2. The CHC90 PWG with PT100 Beta pulse tube inside cryostat.

Regenerator

The regenerator was made from a stack of 1000 stainless steel 400 mesh screens. The screens were cut into rings from sheet with EDM. The outer diameter was 56 mm, inner diameter 27 mm and length 60 mm.

Cold Heat Exchanger

The cold heat exchanger was machined from a copper billet. Slots were cut with EDM to provide passages for the working gas to flow through. Tapered fins of copper remain to transfer heat from the copper block to the helium working gas.

Flow Straighteners

The flow straighteners were made from a stack of 100 mesh brass discs 2 mm thick and were placed at either end of the pulse tube to provide a uniform flow of gas in the pulse tube.

Pulse Tube

The pulse tube was manufactured from G10 epoxy with 3mm thick walls. Even at 3mm thick the G10 walls had less axial conductive loss than the equivalent thin stainless steel tube. G10's low thermal conductivity also acted to insulate the pulse tube gas temperature gradient from the different gradient in the adjacent regenerator. The pulse tube was 21 mm inside diameter and 94 mm in length.

Inertance Tube

The inertance tube started with a 4.3 mm drilling through the water cooled aluminum PWG top plate. The remainder of the inertance tube was formed from copper tube with several tube diameters and lengths tested to optimize the cooling performance of the cryocooler. An inside diameter of 4.3 mm with lengths of 2.4, 2.8 and 3.2 m were tested, as well as an inside diameter of 5.95 mm with lengths of 3.5, 4 and 4.5 m. The results of the inertance tube testing are graphed in the results section of this paper.

Reservoir

The PWG's 2.5 litre gas spring was used as the reservoir. A small pressure wave was experienced in the gas spring, but experience from previous pulse tubes has shown to have a negligible effect on the performance of the cooler.

Insulation

The cryostat held a vacuum of 10^{-7} mbar and Multi Layer Insulation (MLI) was used to insulate the coldhead, heaters, and thermometer.

RESULTS

The cold-head temperature was measured with a four wire silicon diode thermometer and Lakeshore 218 monitor. Cooling power was applied and measured with a 4 wire connection to a single 25 Ω resistor that was screwed directly to the cold-head. Pressure was measured in the PWG compression space, and the displacement was measured using an eddy-current transducer on the back of the diaphragms driving piston. A Labview® high speed data acquisition system was used to calculate PV power and acquire data. A motor controller was used to vary the frequency of the PWG drive motor (3 kW ABB), and also provided input power measurements.

Experiments were conducted to determine power versus temperature performance and efficiency. Cool-down times of 10 minutes to 77 K were achieved, with 120 W @ 80 K and the lowest no-load temperature recorded was 31.9 K at 47 Hz and 2.4 MPa charge pressure (this temperature was achieved with a different inertance tube to the high power optimization). Thermal losses were measured as a comparison to our previous inline and coaxial pulse tubes and were found to be similar at 15 W @ 90 K of heat leak on the non-running machine with warm-up under power[3, 4, 7]. Two diameters with three lengths for each diameter were tested, the results of which proceed.

4.3 mm ID Inertance Tube Optimization

Based on prior experience of our Sage model not relating accurately in practice to the inertance tube length, the inertance tube was optimized experimentally. Figure 3 show a graph of the 4.3 mm internal diameter inertance tube length optimization. Three lengths at 400 mm increments were tested to determine the effect on pulse tube cooling performance with respect to the operating frequency. The peak cooling power at 77 K is achieved between 50 and 60 Hz with the 4.3 mm inertance tube. The best cooling power at 50 Hz is achieved with the 2.8 m long inertance tube. The 2.8 m tube produces its best cooling power at around 53 Hz. A 3 m tube would be the next length to try, given the results shown. The Sage model predicted the optimal length of the 4.3 mm inertance tube to be 2.8 m for 50 Hz, which matches well with the experimental results.

6 mm ID Inertance Tube Optimization

Inertance tubes with 6 mm internal diameter and lengths 3.5, 4 and 4.5 m were tested on the PT100 Beta pulse tube. Using the same method of optimization as was used for the 4.3 mm tube in Figure 3: a frequency sweep was carried out in 5 Hz increments for each of the three 0.5 m incremented lengths. The resulting plot, Figure 4, shows that the optimum length for 50 Hz is 4 m, but the optimum cooling performance is attained at a higher 55 Hz, with a correspondingly shorter 3.5 m inertance tube.

Figures 3 and 4 suggest that an optimum diameter inertance tube for the 50 Hz operating frequency would be slightly smaller than the 4.3 mm tube, since its optimum performance from the best length peaks at 53 Hz and the peak performance of the 6 mm tube appears to be higher than 60 Hz.

The input power for the larger diameter 6 mm inertance tube was also higher for a given cooling power, suggesting that an optimum efficiency could be established, which might not correspond to the peak cooling performance at 50 Hz. The larger diameter tube shifts the optimum frequency up for a given inertance tube length. A next stage in the development may include a Sage mapping of the inertance tube diameter and length to test the strength of correlation to the experiment, with the goal of minimizing the number of resource consuming experiments.

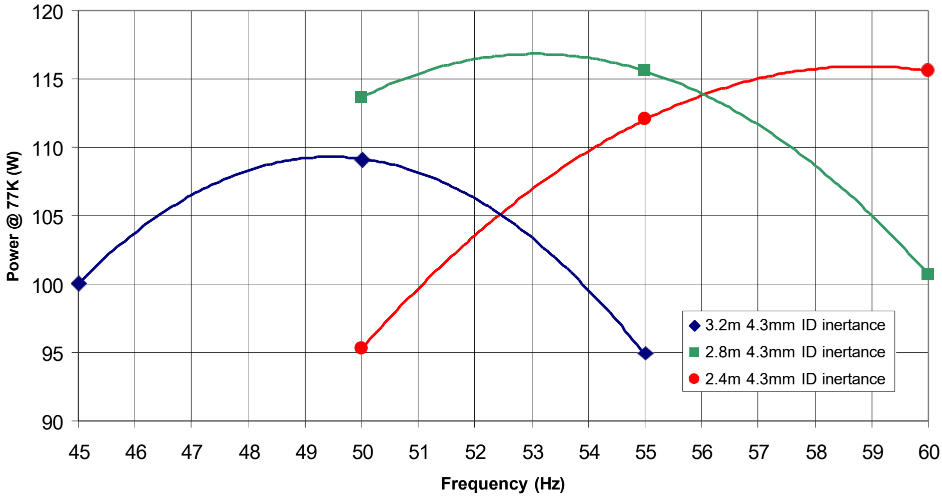

Figure 3. 4.3 mm diameter inertance tube length experimental optimization

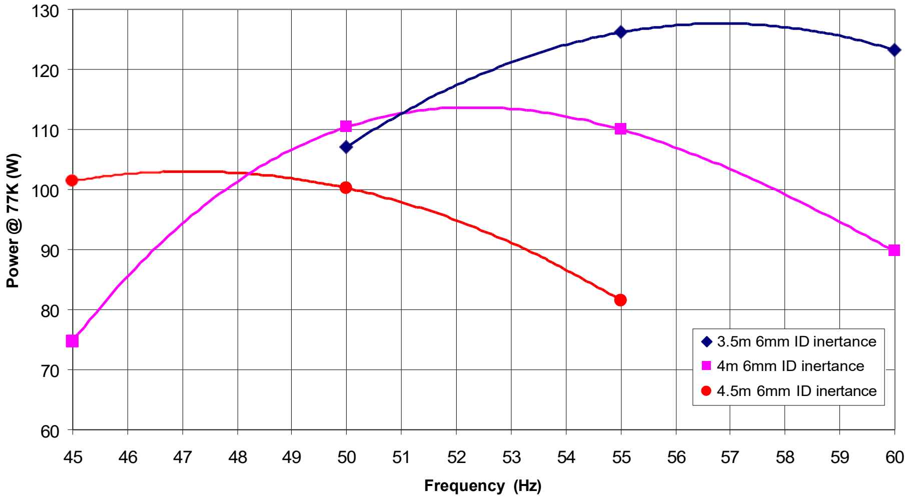

Figure 4. 6 mm diameter inertance tube length experimental optimization

Figure 5 shows the PT100 Sage model power versus temperature curve compared to the experiment. The conditions used for both the model and the experiment were: 2.5 MPa mean gas pressure, 2.8 m long 4.3 mm diameter inertance tube (optimum in both simulation and in practice), and other parameters were chosen to be as close as possible. The cryocooler outperformed the simulation by one or two watts through the entire curve.

Experimental efficiency curves are displayed in Figure 6, and show the percentage of Carnot efficiency of just over 22 % @ 80 K. An electrical input power of 3.1 kW was measured at 80 K for the 120 W of cooling power, which corresponds to the 10.5 % of Carnot based on the electrical input. The PWG efficiency was impaired by the assembly with tighter than required journal bearing clearances and therefore improvements are expected with further work in this area.

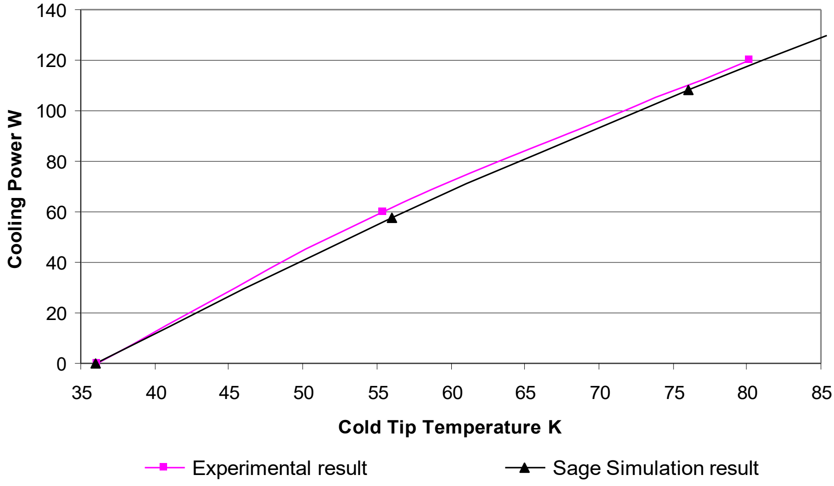

Figure 5. PT100 Beta Sage simulation comparison with experimental run

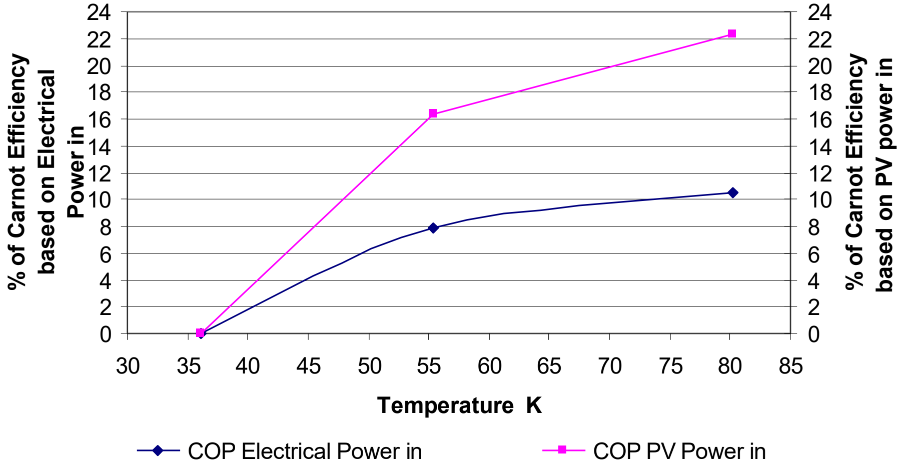

Figure 6. PT100 Beta Cryocooler efficiency

CONCLUSIONS

A beta coaxial pulse tube has been designed, built and tests have been conducted. Sage pulse tube software was found to be very useful for the initial design of the fluid and thermal parameters. The Sage model predicted 120 W of cooling power at 80 K and this was achieved in practice from the pulse tube cryocooler. The cryocooler was optimized for running at the 50 Hz mains grid frequency in New Zealand. Efficiencies at 80 K were 22% of Carnot and 10.5% of Carnot for the PV and electrical input power respectively. A lowest no-load temperature of 31.9 K was achieved with a longer inertance tube and 47 Hz frequency. Inertance tubes of two diameters and three respective lengths were tested. It was found that both the diameter and length need to be optimized to achieve the best performance at a given frequency.

ACKNOWLEDGEMENT

The authors acknowledge Industrial Research Ltd, New Zealand for continued support of this work, New Zealand's Ministry of Science and Innovation for funding, David Gedeon for his Sage software and excellent support and HTS-110 for supporting the commercialization of the device.

REFERENCES

1. Caughley, A.J., Haywood, D., Wang, C., "A Low Cost Pressure Wave Generator using Diaphragms," *Adv. in Cryogenic Engineering*, Vol. 53, Amer. Institute of Physics, Melville, NY (2008), pp. 1122-1129.
2. Caughley, A.J., Emery, N., Glasson, N.D., "Diaphragm Pressure Wave Generator Developments at Industrial Research Ltd," *Adv. in Cryogenic Engineering*, Vol. 55, Amer. Institute of Physics, Melville, NY (2010), pp. 695-702.
3. Emery, N., Caughley, A., Glasson, N.D., Tucker, A.S., "Development of a High Frequency Pulse Tube," *Cryocoolers 16*, ICC Press, Boulder, CO (2011), pp. 175-182.
4. Emery, N., Caughley, A., Glasson, N.D., Meier, J., "Co-axial Pulse Tube for Oxygen Liquefaction," *Adv. in Cryogenic Engineering*, Vol. 57, Amer. Institute of Physics, Melville, NY (2012), pp. 183 – 189.
5. Tanchon, J., Absolut System Internal Report 2012
6. Gedeon, D., *Sage User's Guide, Stirling, Pulse-Tube and Low-T Cooler Model Classes v8 Edition*, Gedeon Associates, Athens, OH, 2011.
7. Yuan, J., Maguire, J., "Development of a Single Stage Pulse Tube Refrigerator with Linear Compressor," *Cryocoolers 13*, Kluwer Academic/Plenum Publishers, New York (2005), pp. 157-163