Large Pulse Tube Developments

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ABSTRACT

Callaghan Innovation, formally known as Industrial Research Ltd (IRL), has continued to develop its largest of three high frequency single-stage pulse tubes. The target performance for the pulse tube cooler is 250 W @ 77 K. The pulse tube is close-coupled to a 200 cc metal diaphragm Pressure Wave Generator (PWG). The previous pulse tube achieved 110 W of cooling power @ 77 K, with an electrical input power of 3.1 kW from a 90 cc swept volume PWG. The pulse tubes have all been tuned to operate at 50 Hz, with mean helium working gas pressure of 2.5 MPa. Sage pulse tube simulation software was used to model the latest pulse tube and predicted 280 W of cooling power @ 77 K. The pulse tube cryocooler was designed to be an intermediate step to up-scale pulse tube technology for our 1000 cc swept-volume PWG, to be used for liquefaction of gases and cooling of HTS applications. Details of the modeling, design, development and experimental results are discussed.

INTRODUCTION

Callaghan Innovation, formerly Industrial Research Ltd has designed and built its third generation of high frequency single-stage co-axial pulse tube cryocoolers. The pulse tube technology has utilized an in-house developed metal diaphragm pressure-wave generator (PWG) technology. The PWG technology developed offers an industrial solution for providing a pressure-wave to a cold-head. Metal diaphragm PWGs have allowed fast development of pulse tubes, from a design concept to an optimized prototype, due to the mechanical drive allowing a fixed displacement over the full operating frequency range. Our previous pulse tube cryocooler prototype demonstrated 110 W of cooling power @ 77 K, with 3.1 kW of electrical input power from a 90 cc swept-volume PWG, running at 50 Hz with 2.5 MPa working gas pressure. A pilot production of three nominally 100 W at 77 K units were produced based on the prototype[1], the first of which has gone into service in a nitrogen liquefier for a New Zealand customer.

The design target of 1 kW @ 77 K came from the needs of small scale industrial liquefaction and High Temperature Superconducting (HTS) applications. We have successfully demonstrated 20, 60, 90, 200, 240 and 1000 cc swept volume PWG's[2-5]. A diaphragm Stirling cold-head is also in development at Callaghan Innovation for use in our PWG technology and is being presented at this conference. Pulse tubes are challenging to scale up [6] due to various regions where instabilities in the working gas flow and internal thermodynamics can cause poor performance. The risks of very large pulse tubes were mitigated by using multiple, smaller, cold-heads on a single PWG. The first step was to develop a single pulse tube close-coupled to a 200 cc PWG, with the aim to manufacture multiple pulse tubes of similar design to be close-

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

coupled to the 1000 cc PWG. The pulse tube was named the PT250, 250 being the nominal cooling power at 77 K when run on a 250 cc PWG. Four 250 W pulse tubes would be mounted on the single 1000 cc PWG to achieve 1000 W of refrigeration,. This paper documents a continuation of last year's developments[6] and describes the modeling, design, and further developments of the PT250 pulse tube.

MODELING AND DESIGN

The design of the pulse tube was based on the previous 100 W @ 77 K single-stage co-axial pulse tubes [1,7,8], and prior experience[9] with similar output in-line single-stage high frequency pulse tubes. The pulse tube and regenerator lengths remained similar to those of the 100 W pulse tube cryocooler as the lengths were primarily a function of frequency. The cross sectional areas, however, were roughly doubled to account for the increase in flow and power. The result was that the length-to-diameter ratio for the 250W pulse tube was significantly smaller than for the 100 W pulse tubes. The after-cooler and cold-head heat exchangers were longer than for the 100 W model; the former due to needing a thicker aluminum plate to safely hold the gas pressure with a larger diaphragm diameter, and the latter due to the increase in diameter of the regenerator with respect to the pulse tube diameter. Sage[10], an industry standard one-dimensional frequency domain modeler developed for Stirling and pulse tube systems, was used to model the PT250 pulse tube. A Sage model was constructed to simulate and design the cold-head, with the target of 250 W @ 77 K with approximately 3.5 kW of PV input power, just over double the cooling power from just over double the PWG size of our previous cryocooler. Figure 1 shows the Sage prediction of cooling power and PV input power versus the cold-head temperature. Several design iterations were performed to achieve the best compromise between the manufacturability of the physical components, cooling power and efficiency. Sage predicted 280 W of cooling power at 77 K from 3380 W of PV power, a pressure ratio of 1.37, and Carnot efficiency of 23.5%. The CAD model in Figure 2 shows the final design of the pulse tube assembly. The after-cooler was water-cooled using a chiller set at 298 K.

MANUFACTURE

Components for the pulse tube prototype were manufactured using typical manufacturing processes, such as Electron Discharge Machining (EDM) for the regenerator mesh, slotted after-cooler and cold heat exchangers, and CNC milling and turning for most of the parts. It was found that the EDM process on the cold-head posed a challenge due to the wire needing to span over

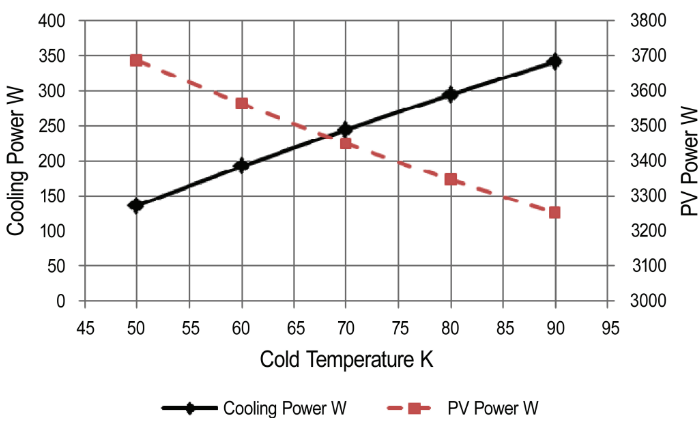

Figure 1. Sage model simulation output for the PT250: 50 Hz operating frequency, 6 mm internal diameter inertance tube, 2.5 MPa Helium working gas pressure

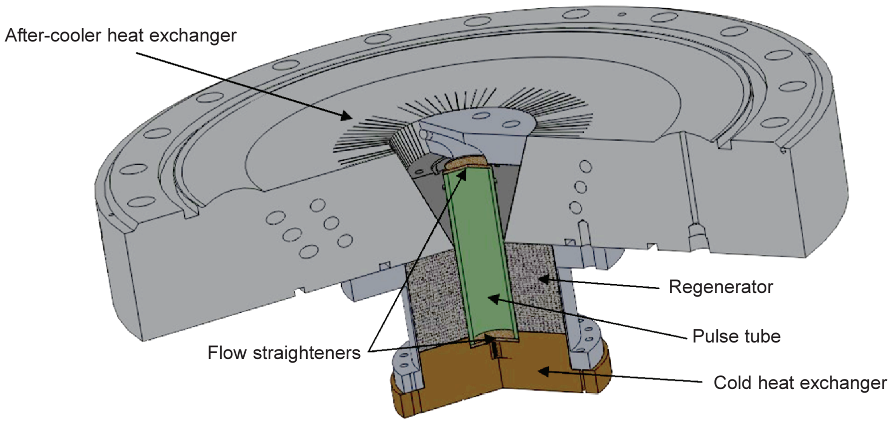

Figure 2. CAD model cut view of the PT250 co-axial pulse tube

100 mm. The pulse tube component was made from a low out gassing glass fiber composite material. 400-mesh stainless steel gauze was EDM cut into 1000 annular discs to make the co-axial regenerator and 100-mesh brass gauze provided the base material for the flow straighteners, situated at each end of the pulse tube. Given the known challenge[11] associated with developing good performance from a very large pulse tube, bolted joints were used at each end of the stainless steel regenerator tube to allow easy change-out of components; an indium seal was used at the cold end and a conventional Viton O-ring at the warm end. The cold-head was made from Cu110 copper. The after-cooler was integrated into the pressure vessel end plate and made from 6061 T6 aluminum, for good heat transfer and mechanical strength. Figure 3 shows the 250 W pulse tube close-coupled to the 200 cc PWG.

TEST SETUP

Copper was used for the inertance tube to allow easy forming. The inertance tube was kept as straight as possible to provide a consistent flow path for the helium gas that oscillates within it, at approximately 50 Hz operating frequency.

The cryocooler was instrumented with a 4-wire Lakeshore Silicon diode temperature sensor, with thermally anchoring bobbin, coupled to a Lakeshore 218 temperature monitor logged cold-

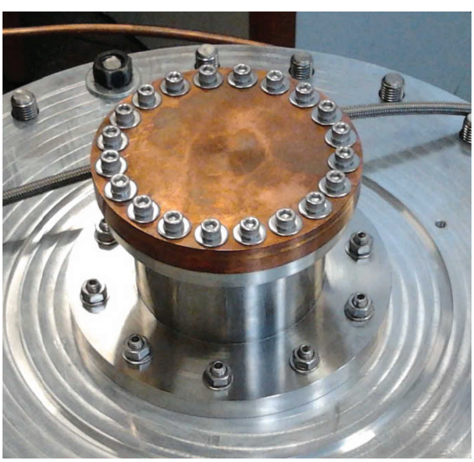

Figure 3. PT250 prototype single-stage co-axial pulse tube

head temperature; a pressure transducer was used to monitor compression space gas pressure; and an eddy-current transducer on the back of the diaphragm's driving piston was used to provide piston displacement and swept volume. A variable-speed drive motor-controller was used to vary the PWG motor frequency. Heat load was applied through an electrical resistor on the cold-head, with a 4-wire configuration to measure the power. The power wires were sized to optimize losses from joule-heating and thermal leak down the wires. Near ambient temperatures such as after-cooler, inertance tube and coolant were measured around the cryocooler using PT100 thermometers.

Data was captured from the sensors using a National Instruments data acquisition (DAQ) system and LabVIEW software, configured specifically for the cryocooler development work. The DAQ system was configured to allow automated running of tests that involved frequency and power changes. A cryostat was made specifically to vacuum insulate the cold-head, and multi-layer insulation (MLI) blanket was used to shield the cold-head and temperature sensor from radiation heat transfer.

The cryocooler is shown in Figure 4, with the PT250 pulse-tube in the MLI and vacuum insulated cryostat, all directly mounted on top of the 200 cc metal diaphragm PWG.

EXPERIMENTAL RESULTS

Previously reported developments on the PT250 pulse tube[7] yielded performance of 31 W @ 77 K with a 6 mm diameter x 3 m long inertance tube, from 930 W of PV power at 35 Hz operating frequency. The Carnot efficiency was 9.65 %, based on PV power. Developments since those results include: an increase in the inertance transition hole from a diameter of 6 mm to 8 mm, optimization of the number of brass meshes in the warm flow straightener and trial of 2 mm thick nickel foam instead, optimization of the number of brass mesh discs in the cold flow straighteners number of brass meshes and trial of 2 mm thick nickel foam, optimization of the number of regenerator meshes and an increased transition hole size from the inertance tube to reservoir, and a ball valve at the reservoir end of the inertance tube. Inertance tube lengths and diameters were mapped for each experiment to find the optimum cooling power. The brass mesh performed better than the nickel foam and less regenerator mesh also performed best for the configuration that was tested.

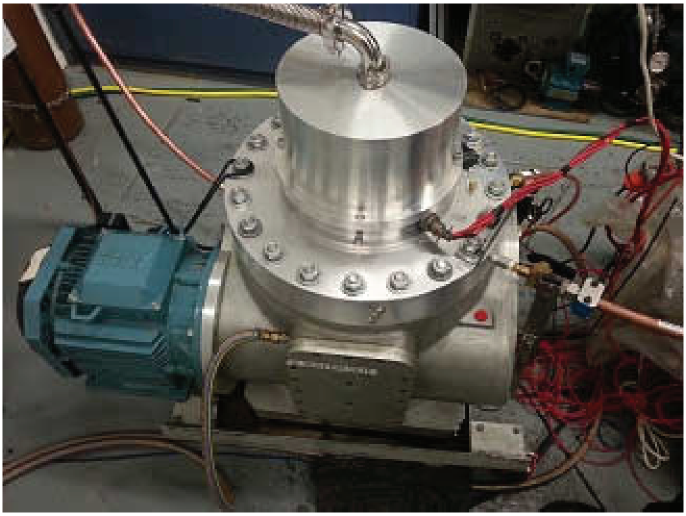

Figure 4. Prototype cryocooler: 200 cc PWG with co-axial pulse tube

We had an advantage in the tuning of the inertance tube because we were able to easily vary the PWG drive motor speed using an off-the-shelf variable speed drive and quickly found the optimum speed for the given tube length/diameter. We discovered the existence of a relationship between inertance tube length and frequency, in most cases a 0.5 m length change corresponded to about 5 Hz of frequency shift, which aided in reducing the number of tests required to determine the best performance. We found that running 3 inertance tube lengths at the previous experiment's best diameter, followed by the previous best length at a diameter either side of the previous best diameter allowed us to determine if the inertance tuning needed re-optimization.

Figure 5 shows a cooling power and PV power against cold temperature plot. The best result achieved was 63.9 W @ 77 K from PV power of 1380 W and pressure ratio in the compression space of 1.26 at a frequency of 46.25 Hz. The Carnot efficiency of 14 %, based on PV power, was encouraging.

When a restrictive fitting that connected the inertance tube to the reservoir volume was removed, the expected increase in performance was not realized - instead a reasonable decrease in cooling power was observed. Furthermore, it was possible to optimize performance with a ball valve at the inertance to reservoir transition. At about the same time it was realized that the inertance tube diameter was much larger than initially anticipated by the Sage model, which led to investigation of the pulse tube end of the inertance tube.

A 6 mm diameter hole transitioned from the pulse-tube (diameter 35 mm) to the inertance tube (diameter 17 mm). The hole size could only be increased from 6 mm to 8 mm due to the space constraints of taking the inertance tube transition hole through the flange. The 8 mm diameter hole has an area of 50 mm^2, which is almost double the previous 6 mm diameter hole of area 28 mm^2. The current best inertance tube internal diameter is 17 mm has an area of 227 mm^2 and is almost 5 times the area of the 8 mm diameter transition hole. A ball valve was placed between the transition hole and the inertance tube to determine the effect on PV power, closing the valve created a decrease in PV. The relatively small transition hole size could be a restrictive area of this pulse tube limiting the PV power for all the experiments. Further work could include placing another inertance tube hole 180^o displaced from the existing with a re-joining of the two inertance tubes back into a single inertance tube to the reservoir. Another fix would be to replace the top flange and integrated after-cooler with a new top flange/after-cooler that incorporates a larger inertance tube transition hole, and more ideally one that can be varied in diameter.

The ball valve that was placed at the reservoir end of the inertance tube optimized the cold-head temperature. The optimized valve position consistently produced an input PV power of around 1300-1400 W, regardless of the configuration. The ball valve at the reservoir end increased the PV power as it was closed off. Current thinking is that either the valve will

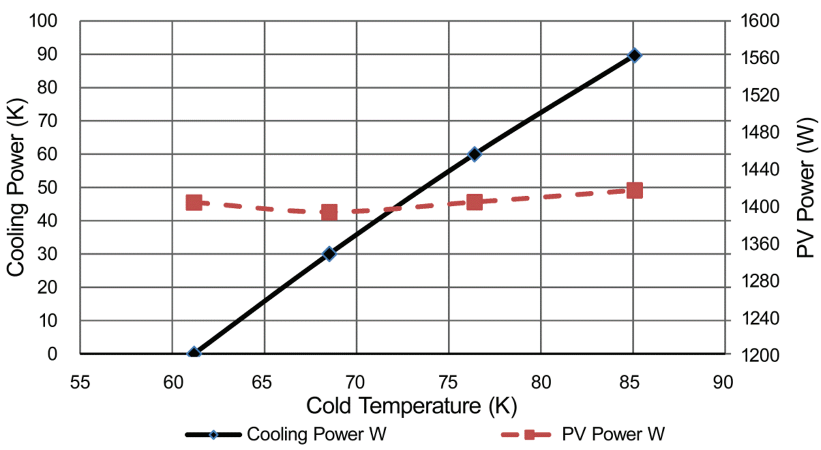

Figure 5. PT250 cooling power and PV power versus temperature

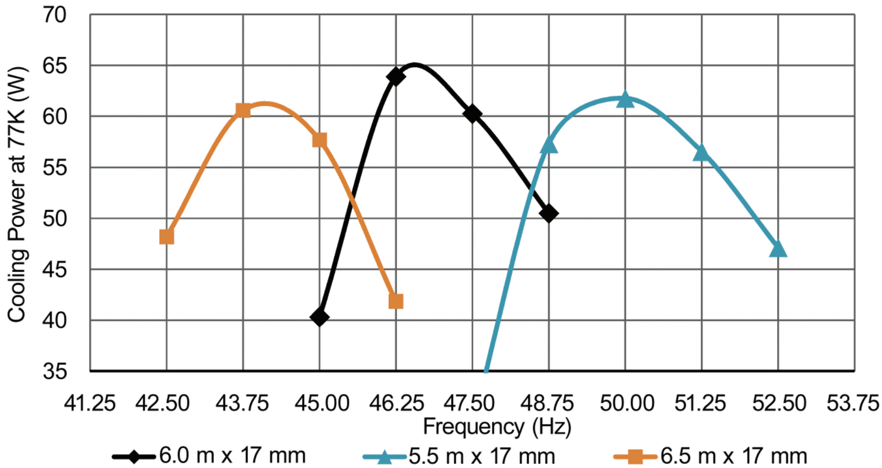

Figure 6. PT250 inertance tube length experiments

improve performance on any pulse tube, or it is a necessary component due to another effect such as the inertance transition hole restriction.

Figure 6 shows an optimization with 3 lengths of the 17 mm ID optimum diameter inertance tube. Each curve was quite sensitive to frequency and the larger the diameter inertance tube the more sensitive the cryocooler was to frequency. The sensitivity may be due to lower flow losses in the larger inertance tubes.

The Sage model was updated to reflect the developmental changes carried out in the experimental optimization. The model still predicts similar performance to previously predicted, which may mean that the reason the experimental performance is lower than expected could be due to phenomena not modelled in Sage, such as 3D flows.

Regenerator and pulse tube length optimization could yield further performance gains, however the two lengths are tied together in the co-axial design meaning that both lengths would need to change by the same amount.

CONCLUSIONS

Callaghan Innovation's developments of the PT250 pulse tube have led to a doubling of the output power at 77 K from our best previously documented result. We have now achieved 63.9 W @ 77 K. The previous best was 31 W @ 77 K, with our Sage model predicted cooling power of 280 W at 77 K at 50 Hz operating frequency. It is possible that the reason the Sage model does not predict the experimental performance is the prevalence of 3D effects. A limit in the PV input power seems to have been reached at 1400 W, which may be due to the inertance transition hole having a much smaller area than the pulse tube and inertance tube. Further developments could include increasing the area of inertance tube that transitions between the pulse tube and the inertance tube. One of the disadvantages of the co-axial design is the difficulty and expense in changing the inertance transition hole size. We have determined that increasing the transition hole size allows greater PV power to be obtained. Pulse tube and regenerator lengths could be changed together to determine an optimum length for those components.

ACKNOWLEDGMENTS

The work carried out for this paper was supported by Callaghan Innovation, the Ministry of Business, Innovation and Employment and Fabrum Solutions.

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