Large Co-axial Pulse Tube Preliminary Results

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Abstract. We report that Callaghan Innovation, formally known as Industrial Research Ltd (IRL), has designed and built its largest of three high frequency single-stage co-axial pulse tubes, closely coupled to a 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 a mean helium working 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 nominal 250 W cryocooler was designed to be an intermediate step to up-scale pulse tube technology for our 1000 cc swept-volume PWG, to provide liquefaction of gases and cooling for HTS applications. Details of the modeling, design, development and preliminary experimental results are discussed.

Keywords: Pulse tube, Sage, pressure wave generator, cryocooler, liquefier, HTS.

PACS code are missing

INTRODUCTION

Callaghan Innovation, formerly Industrial Research Ltd has designed and built its third generation of high frequency single-stage co-axial pulse tube cryocooler. 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. The metal diaphragm PWG's have allowed fast pulse tube turn-around from a design/model concept to a tested, tuned, prototype demonstrator due to the driving diaphragms 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 units were produced based on the last demonstration unit [1], the first of which has gone into service in a nitrogen liquefier for a New Zealand customer.

Small scale industrial liquefaction and High Temperature Superconducting (HTS) applications have highlighted a need for 1 kW @ 77 K from an industrial style cryocooler, which has driven us to that design target. We have successfully demonstrated 20 cc, 60 cc, 90 cc, 200 cc and 240 cc PWG's [2–4], with a 1000 cc PWG in development, to serve 1 kW pulse tube or Stirling cold-heads, also being presented at this conference. Pulse tubes are challenging to scale up [5] due to various regions where instabilities in the working gas flow and internal thermodynamics can cause poor performance. We chose to mitigate some of the large scale risks by using multiple cold-heads on a single PWG. The first step was to develop a single pulse tube close-coupled to our 200 cc PWG, with the aim to manufacture multiple pulse tubes of similar design to be close-coupled to the 1000 cc PWG. The pulse tube was named the PT250, with PT being an acronym for pulse tube and 250 being the nominal cooling power at 77 K, if run on a 250 cc PWG (aiming for 4 x 250 W pulse tubes on the 1000 cc PWG for a total of about 1 kW of cooling @ 77 K). This paper describes the modeling, design, development and methodology behind the PT250 pulse tube.

MODELING AND DESIGN

The design of the pulse tube was based on prior experiences [6] with similar output in-line single-stage high frequency pulse tubes, as well as our own experiences with our previous 100 W @ 77 K single-stage co-axial pulse tubes[1], [7], [8]. The pulse tube and regenerator lengths remained similar to the one of the 100 W pulse tube cryocooler, whilst the areas roughly doubled resulting in the respective L/D ratios decreasing to account for the extra power requirements. The after-cooler and cold-head heat exchangers were designed longer, 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.

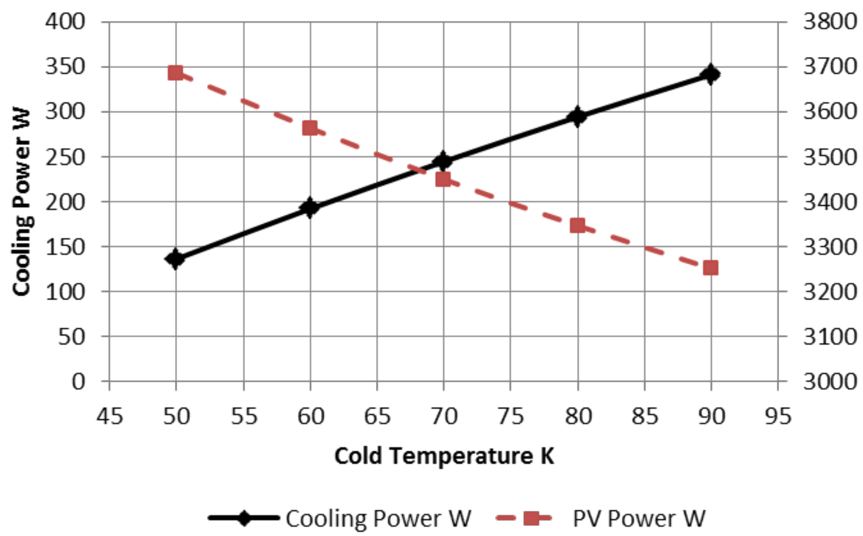

FIGURE 1. Sage model simulation output for the PT250: 50 Hz operating frequency, 6 mm internal diameter inertance tube, 2.5 MPa Helium working gas pressure

Sage[9], an industrial 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 predict cold-head temperature and efficiency, with the requirement to produce around 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 predicted cooling power and PV input power versus cold-head temperature after several design loops to allow the best compromise between the manufacturability of the physical components and the theoretical optimum cooling power and efficiency. Sage predicted 280 W of cooling power @ 77 K from 3380 W of PV power, with 1.37 pressure ratio and 23.5 % of Carnot efficiency. The CAD model shown in Figure 2 shows the final design of the pulse tube assembly. The after-cooler was water-cooled to pull heat from the cryocooler using a chiller set at 298 K, a temperature high enough to avoid condensation buildup on the machine exterior in the laboratory.

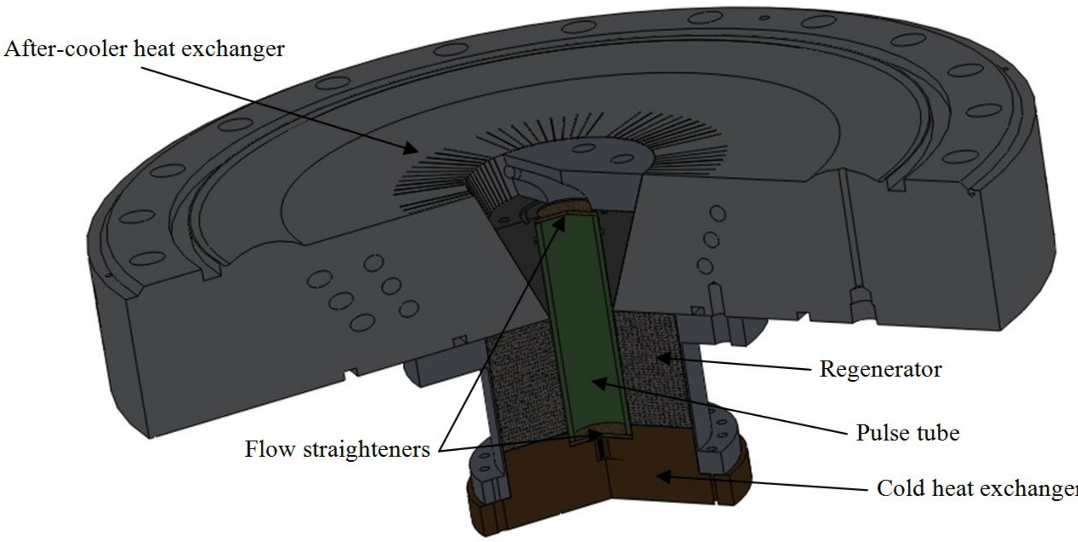

FIGURE 2. CAD model cut view of the PT250 co-axial pulse tube

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, 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 100 mm. The pulse tube component itself was made from a low outgassing glass fiber composite material that was bought in as a prefabricated tube and then cylindrically ground on the outer diameter. 400 mesh stainless steel fabric?? was EDM cut into 1000 annular gauzes to make the co-axial regenerator and 100 mesh brass fabric?? provided the base material for the flow straighteners, situated at each end of the pulse tube. Given the known challenge associated with developing good performance, from what the cryocooler community would consider to be 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 (Cu101 would have provided better heat transfer), and the after-cooler from 6061 T6 aluminum for good heat transfer and also mechanical strength as the after-cooler was integrated in the pressure vessel end plate. Figure 3 captures the 250 W cryocooler in the foreground atop an early 200 cc PWG, with the new in-development 1000 cc PWG in the background, also running a test.

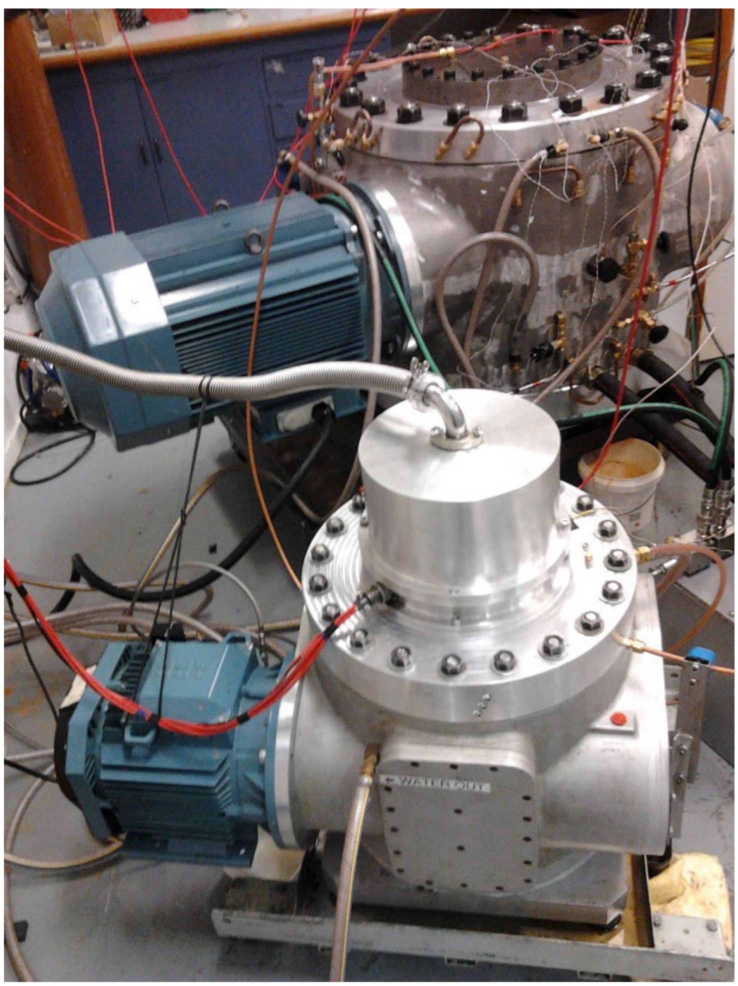

FIGURE 3. Prototype 200 cc PWG with pulse tube in foreground; 1000 cc PWG in background

TESTING

The pulse tube was assembled onto an early prototype 200 cc PWG for experimentation. The usual helium leaks and other minor teething?? problems were quickly overcome, and an initial round of testing was carried out with the cold-head in air to determine if pressure ratio was as expected. The pressure ratio was within the requirement to be less than 1.5. We were also able to visually inspect the frontline around the regenerator tube for even flow in the regenerator. A symmetrical frost line was evident and can be partially seen in Figure 4, which shows an even circumferential temperature distribution.

The cryocooler was then instrumented to allow sensing of various parameters. A 4-wire Lakeshore Silicon diode temperature sensor, with thermally anchoring bobbin, coupled to a Lakeshore 218 temperature monitor logged cold-head temperature; a pressure transducer was used to monitor compression space gas pressure; and an eddy-current transducer on the back of the diaphragms driving piston was calibrated to provide piston displacement and therefore 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, configured 4-wire for measuring 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, although thermocouples would have worked just as well.

We captured data from the sensors using a National Instruments data acquisition (DAQ) system and LabView software, configured specifically for our cryocooler development work. Moreover, 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.

Copper was used for the inertance tube to allow easy forming. The tube was kept as straight as possible to provide the most consistent flow path for the helium gas that oscillates within the tube at approximately 50 Hz operating frequency. Initial testing was carried out with 6 mm and 7.5 mm internal diameter tube.

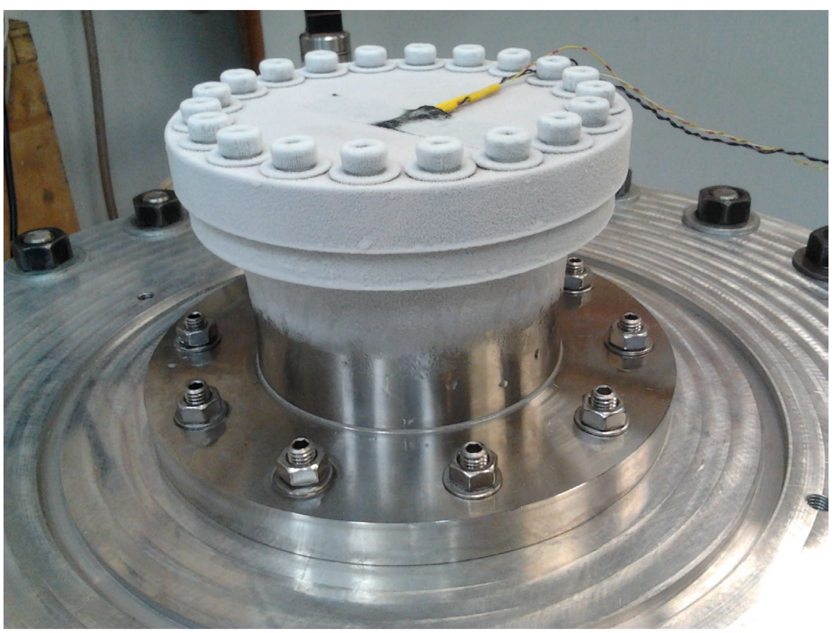

FIGURE 4. Pulse-tube cold-head showing frost line

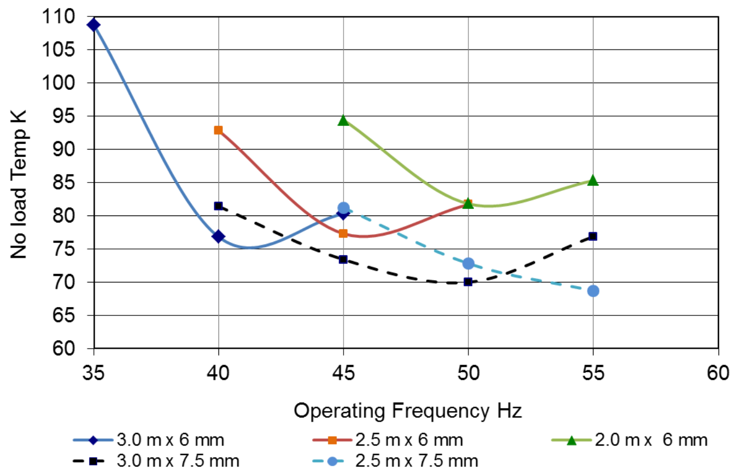

FIGURE 5. PT250 initial inertance tube diameter and length experiments

PRELIMINARY RESULTS

The first power runs from the initial assembly of the cryocooler were encouraging. We tuned the inertance tube with 2 diameters with 2 - 3 length changes per diameter, Figure 5 shows a graph with the inertance tube changes as we tuned for no-load temperature. From Figure 5 it is clear that the optimum no-load temperature occurred at or below 40 Hz for the 6 mm inertance tube diameter, and at or above 60 Hz for the 7.5 mm diameter inertance tube, signaling that an inertance tube between the two diameters might suit best for 50 Hz operation. A best performance of 25 W @ 77 K at 50 Hz was achieved from the 3 m x 7.5 mm diameter inertance tube. We were advantaged in the tuning of the inertance tube in that we were able to easily vary the PWG drive motor speed using an off-the-shelf variable speed drive to quickly find the optimum speed for the given tube length/diameter. We found a relationship between inertance tube length and frequency existed, with a 0.5 m length change corresponding in most cases to about 5 Hz of frequency shift, which aided in reducing the number of tests to determine the best performance.

Some challenges in conducting the experiments then occurred:

- The pulse tube was disassembled and cleaned with acetone after the initial runs. Poor drying from a new vacuum oven that replaced the previously used convection oven, and the larger regenerator gauzes drying on the same size rack as the 100 W gauzes, led to acetone remaining in the regenerator. The acetone residue led to an increase in no-load temperature from 70 K to 170 K. The acetone contamination issue was solved in the short term by going back to the convection oven and laying the regenerator mesh out on a course mesh drying rack.
- A leaking indium seal, due to heating the assembled cold-head during the drying process, required a strip down and replacement of the seal. Since the indium creeps we now torque the cold-head bolted joint each time the cryostat is removed, and no longer plan to elevate the temperature on the bolted cold-head joint.

The challenges mentioned above were resolved and tuning resumed with flow straightener testing. Automation of the testing, which has allowed overnight running will allow more tests to be carried out to help shorten tuning time. A best performance of 31 W @ 77 K from 6 mm x 3 m inertance tube, PV power of 930 W, with 59 K no-load temperature was achieved by removing 10 % of the warm flow straightener material and is graphed in Figure 6. A full set of inertance tuning tests had not yet been completed for the flow straightener change, and were being run at the time of writing this paper. Of interest was the 35 Hz optimum frequency, which was 15 Hz off our required 50 Hz operating frequency. Mapping of inertance tube diameter and length will allow us to tune

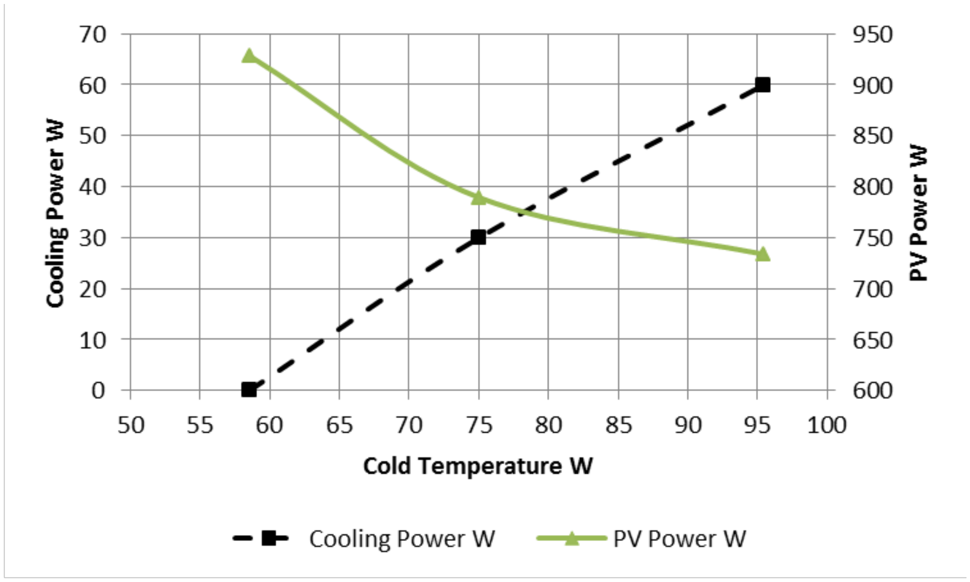

FIGURE 6. Preliminary test result for PT250, cooling power and PV power versus temperature

performance for the higher frequency (larger diameter and shorter length inertance tubes). Further flow straightener and regenerator mesh[6] changes with inertance tube length and diameter mappings at each test point to tune for the best performance with each change are to be carried out.

CONCLUSIONS

Preliminary results are encouraging and experimental development of the PT250 pulse tube continues. Challenges so far included contamination and indium sealing, which have been overcome. Further work includes experimental optimization of the flow straightener thickness and material, and quantity of regenerator mesh. A preliminary best result of 31 W at 77K at 35 Hz and 59 K no-load temperature has been achieved, with our Sage model predicting 280 W @ 77 K at 50 Hz.

ACKNOWLEDGMENTS

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