Advances in a high efficiency commercial pulse tube cooler

Yibing Zhang\textsuperscript{1}, Haibing Li\textsuperscript{1}, Xiaotao Wang\textsuperscript{2}, Wei Dai\textsuperscript{2}, Zhaohui Yang\textsuperscript{1} and Ercang Luo\textsuperscript{2}

\textsuperscript{1} Lihan Cryogenics Co., Ltd., Shenzhen, Guangdong, 518055, China
\textsuperscript{2} Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry of CAS, Zhong Guan Cun Dong Rd.29, Beijing, 100190

E-mail: haibing_li@lihantech.com

Abstract. The pulse tube cryocooler has the advantage of no moving part at the cold end and offers a high reliability. To further extend its use in commercial applications, efforts are still needed to improve efficiency, reliability and cost effectiveness. This paper generalizes several key innovations in our newest cooler. The cooler consists of a moving magnet compressor with dual-opposed pistons, and a co-axial cold finger. Ambient displacers are employed to recover the expansion work to increase cooling efficiency. Inside the cold finger, the conventional flow straightener screens are replaced by a tapered throat between the cold heat exchanger and the pulse tube to strengthen its immunity to the working gas contamination as well as to simplify the manufacturing processes. The cold heat exchanger is made by copper forging process which further reduces the cost. Inside the compressor, a new gas bearing design has brought in assembling simplicity and running reliability. Besides the cooler itself, electronic controller is also important for actual application. A dual channel and dual driving mode control mechanism has been selected, which reduces the vibration to a minimum, meanwhile the cool-down speed becomes faster and run-time efficiency is higher. With these innovations, the cooler TC4189 reached a no-load temperature of 44 K and provided 15 W cooling power at 80K, with an input electric power of 244 W and a cooling water temperature of 23 ℃. The efficiency reached 16.9% of Carnot at 80 K. The whole system has a total mass of 4.3 kg.

1. Introduction
Pulse tube cryocooler was invented in the 1960s. A great deal of research have been done since the middle of the 1980s. Because it has no moving components at cryogenic temperature, the pulse tube cryocooler has apparent advantages over the Stirling cryocooler in terms of reliability, manufacturing cost and capability of undertaking lateral load on the cold finger. The efficiency of pulse tube cryocooler has improved a lot ever since and more and more applications have seen the use of pulse tube cryocoolers.

Founded in 2014, Lihan Cryogenics Co., Ltd. is an international company to design, manufacture and commercialize Stirling type pulse tube cryocoolers. Present models on sale cover cooling capacity from 3W ~ 500W@80K. Among the models, TC4187 has a nominal cooling capacity of 10W@80K with a relative Carnot efficiency of 13%. Compared with a free piston Stirling cryocooler [1], its efficiency still needs to be improved. As is well known, the intrinsic efficiency of an ordinary pulse tube cryocooler is lower than Carnot efficiency because the expansion work inside the pulse tube is generally dissipated as heat in the phase adjusters such as orifice and inertert tube. In order to
improve the efficiency, expansion work must be recovered. Together with Chinese Academy of Sciences, we have successfully developed a hybrid cryocooler TC4282 with a cooling capacity of 20W@80 K, which reaches an efficiency of 24.2% of Carnot [2]. Ambient displacers are adopted therein to replace the inertance tube and reservoir to recover the expansion work as well as adjust the phase. Here we introduce a newest model TC4189, an upgrade of TC4187, which also uses ambient displacers to improve the efficiency.

Besides the efficiency, reliability issue, cost issue as well as run-time control strategy are also important for the cryocooler to be used in the field. To address these issues, several other innovations have also been implemented in the TC 4189, which include a new cold end heat exchanger, a new flow straightening strategy at the pulse tube cold end, a new gas bearing for the compressor piston and a new electronic controller. The following will introduce these innovations in detail, followed by a generalization of the cryocooler performance.

2. Details of the innovations and modifications

2.1. Ambient rod-less displacer

Figure 1. Schematic of three different configurations of cryocooler based on Stirling cycle: a) Pulse tube cryocooler; b) Pulse tube cryocooler with ambient rod displacer; c) Pulse tube cryocooler with ambient rod-less displacer. The black arrow denotes the direction of acoustic work flow as well as the positive direction of x axis. Components: 1. Driving piston; 2. Ambient heat exchanger; 3. Regenerator; 4. Cold head; 5. Flow straightener; 6. Pulse tube; 7. Secondary ambient heat exchanger/flow straightener; 8. Inertance tube; 9. Reservoir; 10. Displacer; 11. Rod; 12. Spring.

Figure 1 compares three different configurations of Stirling type cryocoolers. Figure 1.a illustrates a pulse tube cryocooler inertance tube and reservoir as the phase adjuster. Apparently, there is no work recovery inside the pulse tube. In 2010, Zhu Shaowei et al proposed an ambient displacer structure to improve the efficiency of Stirling type pulse tube cryocooler [3], as illustrated in figure 1.b. In comparison with a conventional free piston Stirling cryocooler, the displacer is shortened and completely put at the ambient end. Functioning of the ambient displacer is optimized by adjusting the displacer mass and area difference on both sides of the displacer. Some theoretical analyses have been carried out. Because two clearance seals are needed for the displacer, a high assembling accuracy is required. In order to ease the assembling process, we adopt rod-less ambient displacer as shown in Figure 1.c for which only one clearance seal exists. In this way, the acoustic power from the pulse tube is recovered to the compression space through the displacer, as denoted by the black arrow, thus marginally improving the overall efficiency.

In practice, TC 4189 uses dual-opposed pistons and a co-axial configuration of the cold finger, as shown in Figure 2. The displacers are also of dual-opposed configuration to minimize the vibration.
The compressor pistons are supported by gas bearings while the displacers are supported by flexure bearings. Typical simulated work flows are shown in the figure, where the angle is the phase difference between pressure wave and volume flow rate.

![Diagram of the hybrid cryocooler TC4189](image)

**Figure 2.** Schematic diagram and photo of the hybrid cryocooler TC4189

2.2. *Innovative cold end heat exchanger*

![Diagram and top view of the cold end heat exchanger](image)

**Figure 3.** Schematic of the cold end heat exchanger:

a) Diagram of heat exchanger; b) Heat exchanger, top view

Generally, for both ends of the pulse tube, flow straighteners are needed to ensure a well-stratified flow inside the pulse tube to avoid jets and reduce mixing losses due to non-uniform flow caused thereby. The flow straightener is normally made by stacking several tens of pieces of screen meshes. This unavoidably causes acoustic power loss. Another possible issue, which is not often mentioned, is that, for a long life time cryocoolers, accumulation of contaminants mostly happens at the coldest area, i.e., the cold end heat exchanger with surrounding area. Through some intended experiments, we found that gas contaminants on these screens easily cause the failure of the cryocooler. To improve the...
immunity of the pulse tube cryocooler to gas contaminants, we decided to remove the flow straightener and use a tapered throat for flow straightening purpose. The shape of the throat has been intensively simulated and optimized by CFD software. As evidenced through experiments, this change has brought no degradation of the cryocooler performance. Another benefit of this change is that manufacturing of tailored screens is no long necessary and no extra parts are required to hold the flow straightening screens in place. This leads to a reduction of the manufacturing cost.

Cold end heat exchanger is a critical component for the output of cooling power. Insufficient heat transfer will deteriorate the cryocooler performance seriously. In our previous practice as well as practices by many other researchers, slot-type heat exchanger made through electric discharge machining (EDM) process has been used. The EDM process is very time-consuming and a thorough cleaning of the debris left in the narrow channels also needs much efforts. Meanwhile, the shape of the narrow channel can be easily distorted due to stresses originating from the process. For this reason, we have put forward a new type of cold end heat exchanger. As shown in Figure 3b, the heat exchanger consists of two mating parts. Both parts are made through the method of hot forging process. When they are put together with a right positioning mechanism, homogeneous narrow channels are naturally established by interleaving of the fins from each part. With well-designed molds, the process could be quick, accurate and greatly improved batch production efficiency. Furthermore, because no debris is produced during the process, cleaning becomes very easy.

2.3. Gas bearing

![Figure 4](image_url)

**Figure 4.** Schematic of gas bearing: a) Conventional design; b) New design;
1. Cylinder; 2. Gas gap; 3. Throttling hole/surface; 4. Piston;

Inside the TC4189, compressor pistons are supported by gas bearings. In a conventional design as shown in Fig 4a, throttling holes are used on the piston to release high pressure gas inside the reservoir chamber to form high pressure gas pads at cylinder surface to support the piston [4]. The throttling hole normally has a diameter of a fraction of millimeter, which is time-consuming to manufacture and can be easily clogged by tiny solid particles, thus leading to the failure of gas bearing and early deterioration of the compressor performance. Here TC4189 uses a porous surface, as shown in Figure 4b to guide the high pressure gas flow, which greatly reduced the possibility of being blocked by solid particles.

2.4. External coil

As is well known, gas contamination is one of the most important factors that limits lifetime of a cryocooler. One of the main sources of gas contaminants is the coil winding and silicon iron stacks. With these components inside the high pressure working space, strict requirements on material selection, baking processes, etc., need to be met. For this reason, we adopt external coil (which is segregated from the high pressure working space) in TC4189 to improve the reliability as well as to simplify manufacturing process, as some other cryocooler manufacturers do [5]. Table 1 compares the performance between the configurations using built-in coil and external coil. When the cooling power is below 15W@80K, the external coil configuration consumes a slightly larger electric power. As cooling power goes higher, external coil configuration even has a lower power consumption than the built-in coil.
Table 1. Performance comparison between the built-in coil and external coil

| Cooling power (W@80K) | Input Power (W)          | Efficiency       |
|-----------------------|--------------------------|------------------|
|                       | Built-in coil | External coil | Built-in coil | External coil |
| 5.4                   | 95.4          | 110.3         | 0.156         | 0.135         |
| 8.7                   | 133.4         | 151.1         | 0.179         | 0.158         |
| 10.4                  | 162.2         | 176.1         | 0.176         | 0.162         |
| 12.0                  | 191.4         | 199.8         | 0.172         | 0.165         |
| 13.7                  | 221.1         | 225.1         | 0.170         | 0.167         |
| 15.0                  | 241.6         | 244.0         | 0.171         | 0.169         |
| 15.4                  | 257.6         | 253.3         | 0.165         | 0.167         |
| 16.7                  | 294.3         | 278.7         | 0.156         | 0.165         |

2.5. Dual Channel Dual Driving Mode Controller

The dual-opposed piston arrangement of the compressor can minimize the vibration of the cryocooler. However, due to inconsistency in the assembling process, the nonlinearity of the magnetic circuit and some other factors, identicalness of dynamic parameters for the dual-opposed pistons can hardly be ensured even with strict requirements on the design and manufacturing processes. Some mechanical vibrations may still exist if no other measures are taken. In order to further reduce the vibration of the cryocooler without extremely high and costly requirements, we decided to drive each side of the compressor motor independently, including the control of both voltage amplitude and phase respectively. The controller electronics automatically gathers and analyses real-time vibration data and output carefully-tuned driving signals to each motor independently.

Furthermore, as evidenced through analysis and experiments, rod-less displacer configuration leads to a lower cool-down speed of the cold finger. To speed up the cool-down process, a control strategy is implemented to drive the cryocooler in the maximum cooling mode during cool-down period, and, when the temperature reaches near the target value, to drive the cryocooler with a nominal voltage.

3. Generalization of the cryocooler performance

Photo of TC4189 is shown in Figure 2b with the key specifications listed in table 2. With the innovations and modifications mentioned in the last section, the cooler performance improved marginally over TC4187. Typically, with a cooling water temperature of 23 °C, a no-load temperature of 44 K and 16.7 W cooling power at 80K, corresponding to a relative Carnot efficiency of 16.9%, are obtained.

The efficiency of the cryocooler are frequency dependent, so we carried out performance test under different frequencies on the TC4189 with a constant driving voltage. The results are shown in Figure 6. It should be mentioned here that the water-cooled ambient heat exchanger changes to be air-cooled here, which leads to a temperature around 40 °C at the surface of the heat exchanger. It can be seen that when the cold head temperature was 60 K or 80 K, the maximum cooling power appears at around 74 Hz, and, when the cold head temperature was 150 K, optimum frequency was greater than 75 Hz.

Figure 5 further shows the measured cooling power vs. cold end temperature with different ambient temperatures and a fixed input voltage of 26 VAC. Cool-down curves with different heat loads at the cold end are shown in Figure 6. The cold head temperature reaches lowest temperature in about 10 minutes. So far, more systematically performance characterization for this newest model, including the vibration tests, is currently underway.

4. Conclusions

TC 4189 is a newest 10 Watt@80K class Stirling type pulse tube cryocooler by Lihan Cryogenics Co., Ltd.. To improve the cryocooler efficiency, improve the reliability, reduce batch production cost as well as improve on-site performance, several key innovations have been made. Under a typical
operating condition with a cooling water temperature of 23 °C, a cooling power of 15 W@80K with 244 W input electric power was obtained, corresponding to a relative Carnot efficiency of 16.9%. Compared with the former model, the efficiency improved by about 30%. As more cryocoolers go into the field in the future, advantages of these innovations will be proved.

| Item                                | Unit | Value  |
|-------------------------------------|------|--------|
| Charging pressure                   | MPa  | 4      |
| Working frequency                   | Hz   | 70     |
| Input power with 10W@80K            | W    | 172.9  |
| Input power with 15W@80K            | W    | 246.7  |
| Operating temperature range         | °C   | -40~70 |
| Geometric dimensions                | mm³  | 192x85x180 |
| Weight                              | kg   | 4.5    |

**Table 2.** Key specifications of TC4189

**Figure 5.** Cooling power vs cold head temperature, constant input voltage of 26VAC

**Figure 6.** Cool-down curves with different heat loads under max piston displacement

**Acknowledgement**
This work is financially supported by the National Natural Science Foundation of China (Contract number 51376187, 51576205).

**References**
[1] RU Unger, DE Keiter, The development of the CryoTel family of coolers, Advances in Cryogenic Engeering, AIP Conference Proceedings 710, 1404 (2004).
[2] Xiaotao Wang, Yibing Zhang, Haibing Li, Wei Dai, Shuai Chen, Gang Lei, Ercang Luo, A high efficiency hybrid stirling-pulse tube cryocooler, AIP Advances, Vol 5, 037127, pp:1-4 (2015)
[3] Shaowei Zhu, Masafumi Nogawa, Pulse tube stirling machine with warm gas-driven displacer, Cryogenics 50, pp. 320–330(2010)
[4] M.Hanes, et al, Performance and reliability improvements in a low-cost stirling cycle cryocooler, Cryocoolers 11, pp.87-95(2001)
[5] M. Meijers, A. A. J. Benschop, and J. C. Mullié, Flexure bearing cryocoolers at Thales Cryogenics, Advances in Cryogenic Engeering, AIP Conference Proceedings 613, 699 (2002)