ABSTRACT

The flexure-bearing technology of Thales Cryogenics BV is being used in an extensive range of pulse-tube and Stirling cryocoolers. Compressors based on this flexure-bearing technology have a high reliability, long lifetime, and low vibrations. They are therefore the compressors of choice for high-end cryocoolers.

Recently, the range of compressors has been extended with a larger compressor, capable of delivering more than 300 W of mechanical power. Apart from the above-mentioned characteristics, this particular compressor model has a high efficiency of more than 85 % at its rated performance.

In this paper, the design validation of this compressor is presented. This includes the verification of the individual loss mechanisms present in linear motor driven compressors.

Furthermore, the potential of this compressor is demonstrated by its application in two cryocoolers. First the performance of a large, 15 W pulse-tube (LPT9710) is presented. The combination of the large compressor with a newly designed pulse tube has resulted in a cooler with an efficiency of up to 15 % of Carnot. Finally, measurements on a combination of the large compressor with a 20 mm Stirling cold finger are presented to demonstrate the potential performance of a – yet to be developed – large-capacity Stirling cold finger.

KEYWORDS: Cryogenics, refrigerator, pulse tube, Stirling, compressor.

INTRODUCTION

THALES Cryogenics BV has been designing and building Pulse-Tube Refrigerators (PTR’s) over the past 10 years. The initial product was based on an in-house developed U-shaped PTR. The current production models of the 1 W and 4 W coaxial pulse-tube coolers (LPT9510 and LPT9310, [1,2]) were developed in cooperation with and produced under license of CEA/SBT (Commisariat à l’Energie Atomique, Service Des Basses temperatures).

Recently [3,4], the range of pulse-tube coolers has been extended with the 15 W pulse-tube cooler, the LPT9710. This cooler is developed and manufactured completely in-house. A photograph of this pulse tube is shown in FIGURE 1.

All THALES PTR’s use flexure bearing compressors that have proven MTTF values far in excess of 40.000 hrs. Field installations at several customers in different
applications - with average running hours for pulse tubes in excess of 68,000 hours - as well as life time tests performed under stringent requirements have proven these reliability figures and thus the reliability of the chosen design concept has been verified [5-8]. Low vibration levels of the compressor are reached without any additional passive or active vibration reduction due to the use of the dual opposed piston concept. These compressor features make, together with the absence of moving parts in the pulse-tube cold finger, the PTR the cooler of choice in applications where long lifetime and low vibrations are very important, or in situations where large masses directly have to be supported by the cold finger. These coolers are typically used in high-end civil applications, such as electronic equipment and sensors for analysis and diagnostics. With the large-capacity pulse-tube, other applications such as pre-cooling for multi-stage, low-vibration cooler chains and (re)liquefaction of liquid cryogens are possible too.

In previous papers the design and optimization of the LPT9710 were presented [3,4]. In this paper, the qualification of the production versions of the compressor and pulse tube are presented, demonstrating the high performance of the system. Second, future applications and extension of the performance of the coolers components are presented. This includes the presentation of preliminary measurements on a Stirling cold finger to demonstrate the potential performance of a – possibly to be developed – large capacity Stirling cooler. Furthermore, upcoming developments in cooler drive electronics are presented, including the performance of Thales’ active vibration reduction electronics implemented in a new generation of cooler drive electronics.

The design and optimization of the compressor has been an important aspect of the development of the LPT9710 cryocooler. Currently, the LPT9710 is the only THALES cooler using this >300W pdV compressor. However, in the near future development of other cryocoolers using this compressor is foreseen. Therefore, the optimization of the compressor as a building block for future coolers is important. Optimization is done to maximize efficiency within the given size requirements. The optimization resulted in the current design of the compressor. In this paper, the high efficiency of the compressor is demonstrated with measurements of the compressors losses.

![Figure 1. Photograph of the LPT9710 coaxial pulse-tube cooler.](image)
DESIGN AND QUALIFICATION

Compressor

The compressor is optimized for performance, lifetime, and cost/manufacturability. Optimization for performance means minimizing losses in the compressor. There are two groups of losses. The first group is associated with the electrical and magnetic design of the linear motors, referred to as dynamic losses. The second group is associated with the hydro and thermodynamic losses, as for instance reported in [9]. The latter are however intrinsic to a certain compressor or cooler layout, and are therefore not included in this optimization. It should be noted, however, that they can limit the efficiency of the compressor beyond what is expected by the dynamic losses. However, they will automatically be included in the overall cooler efficiency.

The dynamic losses consist of the Joule-losses, eddy current losses, and hysteresis losses. Joule losses are caused by the static resistance of the linear motor coils and the current flowing through it. They can easily be determined by measuring the static resistance and the motor current. Eddy-current losses and hysteretic losses are both the result of the alternating magnetic field. Eddy currents are induced in metallic parts due to fluctuations in the magnetic field, causing resistive heating. Hysteresis losses are caused by non-linear behavior of the stator materials. Since they are both caused by the fluctuations of magnetic fields in the metallic parts, they cannot be measured completely independent of each other, without changing the motor configuration. However, it is possible to separate the effects of the magnetic field variations due to the alternating current and the variations due to the moving of the magnet by using different measurement methods. A combination of measurements with either blocked pistons or while operating under vacuum allows the determination of total dynamic losses under different operating conditions, with the current amplitude and piston amplitude as determining factors.

The loss balance of the compressor for two particular configurations is presented below. The first configuration is the combination of the large compressor with a LSF9330 20 mm Stirling cold finger. The second configuration is that of the LPT9710 coaxial pulse-tube cooler. The results for compressor efficiency are presented in TABLE 1. The cryogenic performance of both cooler configurations is reported further on in this paper.

As mentioned, the eddy-current and hysteretic losses cannot easily be separated. Therefore they are combined as one number in TABLE 1. The mechanical power equals the electrical input power minus the two dynamic loss contributions.

The reason why the compressor is slightly less efficient with the Stirling cold head attached is because of the sub-optimal combination. It is not the result of resonance conditions, the compressor is resonant in both situations. However, in order to obtain resonance, the combination with the Stirling cold finger had to run at significantly lower pressure. As a result the different compressor dynamics leads to a different combination of current and piston amplitude, and thus to a different combination of dynamic losses. Nevertheless, the observed compressor efficiencies are very high in both cases.

<table>
<thead>
<tr>
<th></th>
<th>$P_{\text{in, electrical}}$ [W]</th>
<th>$P_{\text{joule}}$ [W]</th>
<th>$P_{\text{eddy+hyst}}$ [W]</th>
<th>$P_{\text{mechanical}}$ [W]</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stirling</td>
<td>175</td>
<td>13.8</td>
<td>11.9</td>
<td>149</td>
<td>85 %</td>
</tr>
<tr>
<td>Pulse tube</td>
<td>300</td>
<td>24.5</td>
<td>18.4</td>
<td>257</td>
<td>86 %</td>
</tr>
</tbody>
</table>
LPT9710 coaxial pulse-tube cooler qualification

In previous papers the design and optimisation of the LPT9710 coaxial pulse-tube cooler was described [3,4]. There, design optimisations were presented on the first prototypes of the cooler. The results of the optimisation were incorporated in the production versions of the cooler. An obvious difference with the prototypes is a reduction in the number of flange connections, replaced by hermetic electron beam welds. Also the cold interface changed slightly, significantly reducing cool down times.

In this section, the qualification of the cooler in terms of power, orientation dependency and vibrations is presented. The average cooling power of the first two production models is shown in FIGURE 2. The skin temperature of the cooler is 45°C, a realistic value for an ambient temperature of approximately 20-25 °C. At skin temperatures of 25°C, cooling power at 80K would increase to more than 17 W. So when sufficient heat sinking is available, for instance in the form of chilled-water cooling, the skin temperature of the cooler can be reduced and the performance increased.

In FIGURE 3 the position dependency of the cooling power is plotted. These results correspond to what was found in the characterisation of the prototypes. The maximum reduction is approximately 3 %. This is less than what is observed at lower-power pulse tubes. The difference is most likely caused by the difference in size, where the larger mass flow amplitude in the pulse tube seems to have a stabilising effect on flow disturbances.

In FIGURE 4 the axial vibrations for two production coolers are shown. They are driven at 350 W input power, the vibrations are measured on the center of the compressor. The different harmonics of the drive frequency can clearly be seen. The variation between the two coolers is due to normal parts and production tolerances. It can clearly be seen that the drive frequency is the dominant vibration source. The higher harmonics are much smaller, in the best performing cooler they are nearly absent.

As outlined later in this paper, the measured vibration levels of this cooler are expected to be reduced by a factor of 50 or more using our active vibration control. A simpler option could be the use of passive vibration control in the form of optimized integration, for instance using dampers. This solution has been tested and showed that vibration attenuation of more than 10 times is possible.
FIGURE 2. Cooling power as a function of cold end temperature for different electrical input powers and a cooler skin temperature of 45 °C.

FIGURE 3. Position dependency of the cooling power. Zero degrees corresponds to cold tip down. Measurement is done at 350 W electrical input power and 45°C skin temperature.

FUTURE APPLICATIONS

Large capacity Stirling coolers

During the development stage, the compressor was combined with an LSF 9330 Stirling cold head. This 20 mm, flexure-bearing supported, Stirling cold finger for space applications was developed within the Cryosystem program [10] and can thus be considered a state-of-the-art Stirling cold finger. This combination of cold finger and compressor is not optimal. The compressor is not designed for resonance in combination with this relatively small cold finger. In order to obtain resonance, the combination was operated at a low filling pressure, leading to sub-optimal operation.
FIGURE 4. Induced vibration spectra for two production version coolers. The two spectra have been separated by 10 Hz in order to make the two spectra visible in one graph.

FIGURE 5. Cooling power of the 9710 compressor with an LSF9330 cold finger as a function of the cold tip temperature, for different electrical input powers. Indicated in the graph is also the performance of the LPT9710 at 350 W electrical input power, and 23°C skin temperature.

Nevertheless, this ad-hoc cooler combination shows a performance of 27 % of Carnot, as shown in FIGURE 5. This is an efficiency that is usually only obtained with high-end coolers, for instance as used in space applications, or kilowatt class Stirling coolers. This cooler obtains similar performance without the advantages of the use of cost-no-object materials (at least for the compressor) nor the advantage of size. For comparison, the performance of the LPT9710 pulse-tube cooler is also included in the plot. The Stirling cold finger reaches the same input power at approximately half the input power.

Based on these results a larger Stirling cold finger could be developed. The design goal for this cooler would be a cooling power of 30 W at 80K, with target efficiency of over 25 % of Carnot.

Drive electronics and vibration reduction

Recently, THALES introduced a new range of Cooler Drive Electronics (CDE) for its tactical coolers [11]. This new range of CDE’s is based on state-of-the-art Digital Signal Processing (DSP) technology, and optimized for minimum size and cost, and maximum efficiency. The DSP ensures maximum temperature stability, while the Pulse-Width-Modulation output amplifiers ensure maximum efficiency. A photograph of the two versions is shown in FIGURE 6.

The output voltage and current of this tactical converter is not sufficient for the LPT9710 cooler. A civil version of this cooler drive electronics is under development. It will be available for all the civil products of TCBV, including the LPT9710. As many of these coolers are used in a lab or industrial environment, it will provide cooler drive and temperature control, supplied by mains power. The CDE is powered from a 28 VDC bus.

THALES has already demonstrated its powerful active vibration reduction electronics [12]. Using a highly flexible algorithm, we have demonstrated continuously adaptive vibration reduction in our previous pulse-tube coolers. The current generation DSP’s, as used in the new family of CDE’s, has become powerful enough to further improve performance in the form of a more suppressed harmonics and increased
resolution in the output signal, whilst integrating the temperature control and output
signal generation in the same compact package.

![Photograph of the HPCDE2465 (foreground) and MPCDE2450 Cooler drive electronics. The HPCDE2465, the most powerful version, provides an output power of more than 100 W within a small envelope.](image)

Unfortunately, during the test phase of the new electronics, only cooler no. 2 from
FIGURE 4 was available for measurements. As this cooler showed only vibrations in
the first harmonic, it was not the best candidate for demonstrating the performance of
the active vibration reduction algorithm. Therefore, the potential performance of the
new electronics was tested on another flexure bearing cooler with clear vibrations
over the first 10 harmonics. The results are shown in FIGURE 7. The active vibration
reduction reduces the first harmonic more than 50 times. The electronics used in this
test is a breadboard version based on the same architecture as the final version.
Future optimization will focus on optimizing software, further improving the
performance of the algorithm.

In these measurements, the vibration reduction electronics were used to minimize the
vibrations at the compressor level. However, given the flexibility of the algorithm, it
can be used to actively reduce vibrations in any location of the application, as long as
any relation between vibrations in that location and compressor excitation can be
determined by the algorithm. The actual transfer function does not have to be known
and is allowed to change over time; this is automatically determined by the active
vibration reduction electronics itself. A technical background of active vibration
reduction can be found in [12].
FIGURE 7. Relative vibration spectra with and without vibration reduction plotted on the same scales. The first harmonic is reduced 50 times by the active vibration reduction.

CONCLUSIONS

In this paper, the newly designed >300 W pdV compressor and the LPT9710 cooler were further presented. The design of both compressor and cold finger are fully qualified and proceeded into series production.

The efficiency of the LPT9710 is nearly 15 % of Carnot, while the combination with a Stirling cold finger showed an efficiency of 27 % of Carnot. The efficiency of the compressor alone is higher than 85 %. Future developments at THALES Cryogenics BV will thus focus on further utilization of this technology in other coolers and applications.

One possible future development could be a large capacity Stirling cooler with 30 W of cooling power at 80 K, with 25 % of Carnot efficiency. Applications of such a cooler can be found in many scientific and industrial applications, including cooling of high-temperature superconductors and (re-) liquefaction of liquid cryogens.

Another future development will be to extent the new range of DSP-based cooler drive electronics for the large power civil applications. After further software optimization, active vibration reduction electronics will be available in almost the same compact hardware package. An LPT9710 cooler fitted with active vibration reduction on the compressor will be perfect candidate for many scientific applications, including pre-cooling in multi-stage, low temperature cooler chains.

References


