Investigation on a single-stage coaxial pulse tube cryocooler for small particle detectors at CERN

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A single-stage coaxial pulse tube cryocooler has been developed for cooling small particle tracking detectors needed for future luminosity upgrades of the LHC. It is designed for remote operation in high radiation areas of the tunnel with restricted space. It features novel phase-adjusting mechanisms integrated into the warm flange. This flange is cooled with ambient air to reach a simple and compact design. The dimensions of the cold-finger are 24 mm diameter and 170 mm length. The measured no-load temperature is 52 K and the pulse tube cryocooler provides a cooling capacity of 5 W at 80 K.

INTRODUCTION

The construction and commissioning of the Large Hadron Collider (LHC) at CERN is close to completion. For the years to come a high-luminosity upgrade program of the LHC and experiments is planned. Some small scale experiments require low temperature cooling for their particle tracking sensors. We propose a combination of heat pipes or loop heat pipes for heat extraction with pulse tube cryocoolers (PTC) as the refrigeration system [1]. Cryogenic heat pipes were designed, have been tested and their suitability in high radiation fields is proved [2]. In contrast to most existing PTCs which operate in laboratory environments, this investigation has as objective to develop a prototype PTC suitable as cold source for the cooling of small detectors in remote and hostile areas at the LHC. The design studies stress simplicity to enhance reliability for the envisaged application. The developments made during the course of the work may be useful for an even wider acceptance in the cryogenic field.

SYSTEMS DESCRIPTION

The past 20 years saw the rapid advancement of the PTC as an efficient and reliable cryocooler. A variety of improvements on its configuration or materials have brought it from a laboratory curiosity to the point where it is now the most practical of all cryocoolers for a given size in the temperature range between about 50 K and 120 K [3-7]. Advantages like less vibration and longer maintenance intervals seem to indicate
that PTCs will supersede Stirling and GM cryocooler and be the next generation of regenerative refrigerators.

At CERN, it is intended to make use of these advantages in supplying low-noise cooling for small particle detectors employed in some LHC luminosity upgrade experiments and, by further development to adapt the design of the PTC to the specific requirements, in particular the harsh radiation backgrounds. All radiation sensitive equipment like electronics, material and equipment that may change characteristics when exposed to ionization or hadronic radiation will be placed at distance. This applies to the compressor set and control system which will be installed at several hundred meters distance in safe areas in case needed. The link to the PTC will be done solely with a low and high pressure line and electric cabling. For the PTC the basic configuration of a coaxial type has been chosen due to its compactness compared to other types.

DESIGN OF THE PTC

The design and optimization of the PTC are based on the theoretical CFD model [8] grounded on the analyses of thermodynamic behavior of the fluid in the oscillating flow regenerators. Care was taken for precise dimensioning of the different parts and, during the fabrication quality control was respected.

![Figure 1 Picture of the compact PTC (left: coaxial cold finger and buffer volume attached to the warm flange; right: with vacuum insulation cylinder)](image)

Figure 1 shows left the inner structure with the cold tip and the integrated buffer vessel and right completely assembled with the vacuum chamber. The length of the cold-finger is 170 mm, the outer diameter of the cold tip is 24 mm and the overall length of the system including the buffer is 320 mm. As shown in the figure, we cancel the water-cooling in order to provide for a simple and compact system. The cooling of the warm end depends only on the convection of the ambient temperature air.

One of the important features of the PTC is the adoption of a novel phase-adjusting mechanism which was developed. It is integrated into the warm-end flange allowing for discarding all the adjusting valves and corresponding connecting tubes necessary for the conventional orifice or double-inlet counterparts [9]. The design also permits to omit the long thin tube used in the inertance-tube type versions. Furthermore,
the buffer is also directly attached to the warm-end flange. These features are the basis to obtain an unmatched compact system [8] and, at the same time, they permit to minimize the dead volume intrinsic in orifice or double-inlet type PTCs and their variations as well [10].

Also the regenerator was designed to be simple in fabrication and no special regenerator matrix materials were used like rare earth or lead spheres. All the matrices are commercially available 316L stainless steel meshes. We have three stages of different mesh size. From cold to warm end along the regenerator; 0.2 of the total length uses 400-mesh with a porosity of 28%, and 0.7 of the length uses 295-mesh with a porosity of 34%, and the remaining 0.1 uses 210-mesh with a porosity of 34%. The average porosity is about 31.2%.

EXPERIMENTAL SET-UP

The experimental set-up is shown in Figure 2. We use a standard commercial GM-type compressor with 3 kW electrical power. The high and low pressure flexible lines connect to the rotary valve and are each 20 m long. The frequency converter of the rotary valve permits variation between 0.8 to 6.0 Hz to investigate its effect on the performance.

![Schematic diagram of the experimental set-up](image-url)
The temperature of the cold tip is monitored by a CLTS thermometer. Four Pt-100 thermometers are placed evenly along the external wall of the regenerator from the cold to the warm end to monitor the temperature profile. Flexible MINCO® thermo-foil heaters are fixed around the cold tip to simulate the heat load and measure the respective cooling power. The oscillating pressure is monitored at the inlet. A laboratory type data acquisition interface permits online display of the experimental data on a central computer.

EXPERIMENTS AND RESULTS

A number of experiments were conducted in systematically varying parameters for performance optimization. We report the effects of the operating frequency and the charge pressure as they have the largest influence on the cooling performance.

The influence of the frequency is directly related to the thermal penetration depth in the solid matrix. For a semi-infinite medium, the thermal penetration depth is given by:

\[
\lambda_t = \frac{k}{c_m \pi f}
\]

where \(k\) is the thermal conductivity, \(c_m\) is the volumetric specific heat and \(f\) is the frequency, i.e. a lower operating frequency can result in a larger thermal penetration depth that causes higher regenerator efficiency. However, the operating frequency is also closely related to the PV work transfer in a working cycle. Therefore, a trade-off must be made between these influencing parameters. The optimum performance was found by experimentation.

The variation of the no-load temperature of the cold tip with frequency is shown in Figure 3. The cooling performance is dependent on the gross cooling power and the dynamic losses in the cryocooler.
The no-load temperature decreases with increasing frequency caused by the increasing gross cooling power (PV work) until the increasing dynamic losses in the regenerator start to dominate (compare Eq. 1). The optimum frequency can be found around 2.27 Hz.

The variation of the no-load temperature with charge pressure is shown in Figure 4. Correspondingly, in the tested charge pressure range from 1.70 MPa to 1.84 MPa, an optimum charge pressure was found at around 1.76 MPa. At this pressure a dynamic pressure ratio up to 3.21 was measured.

The typical cool-down curve is shown in Figure 5. With the charge pressure of 1.76 MPa and an optimum operating frequency of 2.27 Hz, the no-load temperature of the cold head decreases from 300 K to 75 K in 18 minutes, and down to 52 K in 36.5 minutes. The time taken from ambient temperature to liquid nitrogen temperature accounts for less than half of the overall cool-down time. At the same time the temperature of the warm flange rises to 311 K.

The cooling performance is shown in Figure 6. Some typical values are 1.4 W @ 60 K, 5 W @ 80 K or 19 W @ 160 K. The developed PTC can meet the cooling requirements of small particle detectors. Considering its small dimensions, non-optimized regenerator and the air cooling option at the warm end, we believe an optimization of parameters will result in an increased overall performance, tantamount to a lower no-load temperature.

**CONCLUSIONS**

The novel phase-adjusting mechanism employed in CERN's single-stage coaxial PTC together with the integrated buffer volume and air cooling resulted in an unmatched compact system. Further merits include easy fabrication and assembly and, low cost and reliability by design. These features, together with the overall system lay-out and design, make it a promising candidate for the cooling of small tracking detectors in LHC luminosity upgrades where the collider tunnel and detector caverns have very restricted space for equipment.
Despite its simplicity and small size the developed PTC with the novel phase-adjusting mechanism can currently operate from ambient to 52 K and provides 5 W of cooling capacity at 80 K. New experimental investigations are considered with improved parameters and we expect increased cooling performance and a considerably lower no-load temperature limit.

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