RECENT DEVELOPMENTS ON CRYOCOOLERS IN EUROPE

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ABSTRACT

New markets such as high temperature superconductors applications and space applications are requiring new cooling performances, efficiency and high reliability for future cryocoolers . New emerging technologies such as flexure bearings and Pulse Tube have demonstrated potentially interesting capabilities for future generations of cryocoolers. In this paper we present the recent developments performed in Europe in this field.

INTRODUCTION

Since several decades, cryocoolers are commercially available, based essentially on low frequency Gifford Mac Mahon (GM), high frequency Stirling and Joule Thomson (JT) expansion cycles in the 4K to 200K temperature range with cooling powers ranging from a few hundred milliwatts up to a few hundred watts. Few years ago, a 4K low frequency GM type Pulse Tube cooler (PTC) has been commercially introduced in the US by Cryomech [1]. Also, 4He-3He dilution refrigerators are commercially available for ultra low temperatures down to a few milliKelvin. Obviously these commercial products meet well identified applications cooling and operation specifications. GM cryocoolers are essentially integrated in vacuum cryopumps and MRI cryostats. Compact Stirling cryocoolers are widely used in infrared detection modules mostly for military night vision optical systems. JT expansion cryocoolers in open cycles, fed with high pressure gas storage bottles, are mainly integrated in single shoot missile guidance infrared systems. 4K GM cryocoolers, GM type PTC and dilution fridges are common cooling solutions in experimental devices for physicists in Research Laboratories.

Recently emerging applications such as high temperature superconductors based electronic (filters for Telecommunication, AD converters, software defined radio) or electro technical (transformers, fault current limiters, motors and generators rotors, power cables) devices are requiring new performances in terms of operation temperature (25K – 65K), cooling power, reliability, integration and maintenance. Space borne applications (biological samples freezing and preservation on board the International Space Station, earth observation missions, astrophysics instruments) are also requiring high efficiency and reliability cryocoolers able to survive launching conditions even in the ultra low temperature domain.

To meet this new requirements, several technologies have emerged (flexure bearings, PTC, sorption coolers) and are actively developed to provide a new generation of cryocoolers. Ongoing developments performed in this field in Europe are presented here after.

GM CRYOCOOLERS AND GM TYPE PTC DEVELOPMENTS

Large cooling capacity single stage coolers

The emergence of electro technical devices such as fault current limiters, transformers or generators/motors rotors implementing high temperature superconductors technology has induced a need for large cooling capacity cryocoolers in the temperature range from 25K up to 65K. GM cryocoolers and GM type PTC are a potential solution mainly for cooling powers from a few ten watts up to a few hundred watts. Few years ago Cryomech in the US has introduced a new series of large cooling power GM cryocoolers (AL 230 and AL 330) with optimized performances below 50K (introducing lead as regenerative material in the lower part of the regenerator): typically 45W and 75W at 25K and 135W and 260W at 65K for 5.5kW and 7kW electrical input and 60Hz operation.

Leybold [2] has also commercialized such a GM cryocooler (model 120T, 25W at 20K with 6kW electrical input).

The main inconvenients of GM coolers are the level of induced vibrations by the cold head at its operation frequency (from 1Hz to 2.4Hz, depending on the cold head motor and electrical supply frequency 50/60Hz) and the need for periodical maintenance (friction seals) requiring generally to stop and heat up the system (unless complicated or thermally inefficient coupling of the cold head with the thermal load are implemented). The PTC technology, with no moving part in the cold finger, is a promising option to keep clear of these drawbacks.

Giessen University is developing such in partnership with Leybold [3] and Siemens a low temperature, large capacity single stage PTC in its TransMIT-Center of Adaptative Cryotechnology and Sensors. A prototype has demonstrated 20W to 45W (depending on the type - RW4000, 5kW or RW6000, 7kW - and number of Leybold compressors operated) cooling power at 26K, corresponding to a 0,43% COP in the best configuration, comparable with the above mentioned commercial GM cryocoolers. Ultimate temperature as low as 14K has been achieved. This PTC has been used as a liquid Neon condenser to operate a thermo siphon cooling loop for a HTc motor rotor prototype in partnership with Siemens.

At Jena University [4], work is also performed on large capacity GM type PTC. Implementing lead coated stainless steel or bronze wire meshes in the regenerator of a Four Valve PTC, an ultimate temperature of 17K has been demonstrated as well as a cooling power of 40W at 34K (which was the ultimate temperature of this PTR before implementing lead wire mesh) with Leybold RW600 (7kW) compressor.

Multi stage coolers

Multistage GM and GM type PTC in the 4K to 10K temperature range have been commercially introduced by Cryomech and Sumitomo few years ago. A potential large scale use of these coolers is for the thermal shielding and Helium boil-off condensation (or even direct conductive cooling of dry magnets) in medical MRI or research NMR cryostats. Prototypes of such zero boil-off MRI units are under development and tests.

Achieving temperature even below 4K with such mechanical cryocoolers is a challenge of interest for some scientific applications.

Giessen University in Germany is still developing 4K PTCs based on further development of the earlier 4K Giessen PTC. These coolers are built and sold in small quantities. A first prototype has demonstrated a cooling capacity of 0.6W at 4.2K and simultaneously 20W at 65K with a 6kW compressor: it has been used for a 5.5T magnet cooling and is foreseen for precooling 3He sorption coolers. A second prototype has demonstrated a cooling capacity of 0.2W at 4.2K and simultaneously 1W at 68K with a 1.75kW compressor: it has been used for a Josephson Voltage Standard prototype. A new design with independent gas circuits of the two stages allows to operate only the smaller 2nd stage with ^3He: a low temperature T_{min} = 1.27 K has been demonstrated.

Eindhoven University in the Netherlands has designed a three-stage small in size and weight GM type PTC (total volume of the tubes and the regenerator is only 0.28 liter, meaning small amount of working gas and regenerator material). This cooler operates at a frequency of 1.83 Hz and is driven by a 4 kW compressor. The lowest temperature achieved with ^4He is 2.13 K, with ^3He the temperature of 1.73 K has been reached. The cooling power at 4.2K is 80 mW with ^4He and 124 mW with ^3He**.**

STIRLING CRYOCOOLERS AND STIRLING TYPE PTC DEVELOPMENTS

High reliability: flexure bearing technology

To achieve high reliability for demanding applications, it is now commonly agreed that the flexure bearing technology introduced by Oxford University more than a decade ago is a unique feature to ensure the required frictionless operation and clearance sealing in linear Stirling coolers. Several companies in the US (Ball Aerospace, Lockheed Martin, NGST formerly TRW) have developed for space applications specific coolers generally associating a two back to back pistons compressor with an actively driven cold finger, implementing flexure bearings, linear motors and phase shift control electronics.

Thales [5] has undertaken the development and commercialization of a new Stirling cryocoolers series (cooling power ranging from 600 mW up to 2W at 80K) implementing the flexure bearings twin pistons linear compressor with moving magnet motor (reducing risks of cycle gas pollution by motor coil out-gassing and of flying wires and feed-through failures) technology and a pneumatically driven cold finger (reduced complexity: no motor, no active phase shift control electronics). A picture of two cooler types extracted form the LSF coolers family is shown in the Figure 1 and the performances are presented in Table 1.

LSF9180 600 mW @ 80 K / 23°C 40 W input power ∅ 5 mm coldfinger 2.4 kg
LSF9188 1600 mW @ 80 K / 23°C 60 W input power ∅ 10 mm coldfinger 2.4 kg

Table 1: cooler characteristics.

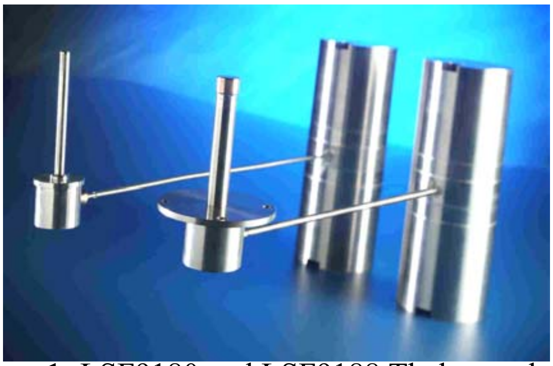

Figure 1: LSF9180 and LSF9188 Thales coolers.

These coolers are intended to offer a high reliability (ongoing endurance tests have already demonstrated more than 28.000 hours of operation without any performance degradation) with selling prices close to those of conventional sliding piston tactical coolers.

In partnership with Thales, based on their flexure bearing technology, Air Liquide has developed a specific Stirling cooler for space applications. The prototype, developed for Cryosystem - a freezer to be flown on board the International Space Station – under ESA funding, implements also flexure bearings on the cold finger and material and design changes in compressor to take into account specific operation conditions in space. Performances (9.3W at 80K with 150W electrical input) are presented elsewhere [6] in this conference.

AIM and Leybold have also recently developed new Stirling coolers implementing flexure spring (not flexure bearing) for the compressor pistons central position and resonant operation control, allowing to reduce radial wear with cylinder as compared to conventional helicoidal spring technology.

Stirling type Pulse Tube Coolers

The main drawback of the Stirling coolers in terms of reliability and integration easiness is their cold finger: the moving displacer technology and the associated linear motor are a potential source of failure and exported vibrations, the reduced clearance between the moving regenerator/displacer and its shelve induces strict mechanical load restrictions on the cold finger cold tip to avoid any internal friction which generally results in very complicated thermal link design, the active phase shift control loop complicates the drive and control electronics.

The PTC technology with no moving part in the cold finger and passive pneumatic phase shift control is recognized as an attractive alternative to Stirling coolers. Recent developments, such as phase shift control by inertance, have greatly improved the PTC temperature stability and overall efficiency which is now comparable with Stirling coolers.

Air Liquide, in partnership with CEA/SBT and Thales has undertaken since several years the development of PTCs. Under European Space Agency funding, a Miniature Pulse Tube Cooler (MPTC) has been recently successfully designed and tested [7, 8]. Typical performances of this MPTC are reported in Table 2 and a picture is shown in Figure 2. The integration of this MPTC in future space missions is under consideration.

Performance	1 W @ 80 K
Input Power	35 W
Frequency	50 Hz
Mass	2.8 kg
Compressor OD	63 mm
Compressor length	157 mm
Cold finger OD	100 mm
Cold finger length	179 mm

Table 2: MPTC characteristics.

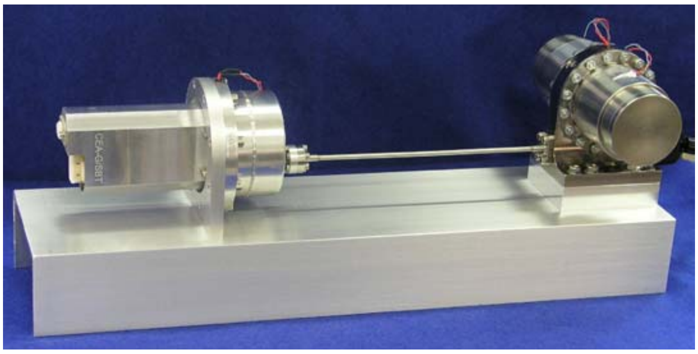

Figure 2: MPTC EM cooler.

The need for larger cooling capacity PTCs has been clearly identified, first for ground based commercial applications (i.e. superconducting filters for telecom) but also for future earth observation or other space applications. Air Liquide and its partners have developed such a larger heat lift capacity PTC demonstrator. The performances achieved are 7.7W at 80K for 200W input power in in-line configuration. U-shape design has been prototyped and a coaxial version is under industrialization at Thales for future commercialization (Figure 3).

Figure 3: U-shape PTC prototype and coaxial shape PTC CAD design.

In the framework of the European SuperADC program, a two staged PTC is also under development by the same partners with the aim to produce simultaneous cooling power at 80K and 20K-30K. Preliminary results have been presented recently elsewhere [9].

Giessen University, in partnership with AIM and Leybold, in a project on "HTS for future telecommunication" supported by the German Government has also developed Stirling type PTCs with medium cooling capacities. U-shaped, inline and coaxial cold finger configurations have been developed and driven either by AIM SL200/400 linear compressor (100W nominal input power) or by Leybold Polar SC7 linear compressor (200W nominal input power). Experimental results are summarized in Table 3 [10].

PTC/Compressor/ Input power	Geometry	No-load temperature (K)	Cooling power @ 80 K (W)	COP @ 80 K
PT03/SL400/100 W	U-shaped	41.3*	3.3*	3.3 %*
PT07/SL400/100 W	Inline	41.9*	3.55*	3.55 %*
PT08/SL400/100 W	Coaxial	36.4*	3.6*	3.6 %*
	Coaxial	49.7	3.3	3.3 %
PT05/Polar SC7/200 W	U-shaped	44.5	7.4	3.7 %
PT04/Polar SC7200 W	Inline	45.0	8.7	4.4 %
PT09/Polar SC7/200 W	Coaxial	47.0	7.4	3.7 %

**) Data marked by * are obtained with 2nd inlet; all other results are with inertance only.*

Table 3: Summary of results (water cooling of warm end at 20 °C)

ILK Dresden has also developed an inertance U-shape PTC (1W:80K/100W electrical) driven by an AIM linear pressure oscillator. A prototype based on an active reservoir principle driven by a rotary machinery implementing a pressure wave generator and an expander is presently under development with a 15W at 80K performance goal.

Large cooling capacity Stirling and Stirling type Pulse Tube Coolers

Large cooling capacity Stirling cryocoolers (1 to 4 kW at 80K for single stage units and several hundred watts at 20K for two staged units) have been developed several decades ago by Philips mainly for Air, Nitrogen, Neon and Hydrogen liquefaction. These cryocoolers with rotating motor for compression piston drive via crankshaft and mechanical expander phase shift control are still commercialized by Cryogenics & Refrigeration B.V. Their technology generates high level of vibration and short interval maintenance.

In view of potential future HTS applications in motors/generators or power transmission cables, the interest for such large cooling capacity Stirling type PTC has been increasing. In the US, Praxair and American Superconductor Company have initiated development programs and demonstrated 200W cooling power at 80K with 4kW electrical input in linear flexure bearing compressors (provide by Clever Fellow Inc. or Stirling Technologies).

In Europe, Air Liquide and Giessen University have recently initiated similar development programs.

JT EXPANSION CRYOCOOLERS

The demand for miniature JT expansion coolers operated around liquid Nitrogen temperature in open loop for infrared modules cooling has been stable during the past years. Few improvements or innovations have been published. A common requirement for these products is the capability to deliver in a first time a large flow for rapid initial cooling down from room temperature and later on to provide the minimal flow required for the detector temperature stabilization. Most of the existing systems are implementing flow control valves with a needle moving in a calibrated orifice and controlled either by gas actuated bellows or axial differential thermal extension based devices. These flow control systems are complicated and expensive to integrate. Air Liquide has developed and patented a new simple and compact system based on the radial differential thermal expansion in an annular geometry.

The use of mixture (freons or hydrocarbons with nitrogen, neon, hydrogen) as cycle fluid in JT expansion close cycle coolers has been an active subject of development in the recent years. The main advantages of using such mixtures (the physical properties of mixture and their potential interest have been extensively described in an old patent from (Refrigerant for a cryogenic throttling unit. V. N. Alfeev. Patent specification N°1.336.892, 1971) is a higher specific cooling power with lower expansion ratio compared to pure nitrogen, allowing for close cycle operation using GM coolers type compressors. A commercial product (CryoTiger) has been introduced by APD few years ago with a few tens of watt of cooling power around 100K. Developments are also progressing at Dresden Technical University in this field [11].

Twente University is performing an innovative work related to JT expansion coolers aimed to develop miniature systems driven by thermal compressors (using sorption/desorption properties of activated charcoal or other types of adsorbent under thermal cycling) for electronic components or detectors cooling. Etching technology is used for counter flow heat exchangers and JT expansion capillary manufacturing. A prototype using Xenon as fluid and charcoal as adsorber has been developed to demonstrate the technology with cooling at 165K, using a Peltier thermo element for precooling [12]. A major interest of this technology is its potential for low vibration (no moving mechanical parts, except check valves operated at very low frequency in the thermal compressor). A development [13] is supported by ESA in the perspective of the future Astrophysics mission Darwin. The goal is to develop a two-stage sorption JT cooler. The first stage (H_2/Charcoal), precooled by the first stage, should reject 3W at 80K (radiator) and provide 25mW cooling at 14,5K with radiative precooling at 50K. The second stage (He/Charcoal) should reject 5W at 50K (radiator) and provide 10mW cooling at 4,5K.

SUBKELVIN CRYOCOOLERS

SubKelvin cooling is mainly required on ground by scientists for laboratory experiences or in space for detectors cooling in Astrophysics missions.

Commercial systems for laboratory use

A double stage ($^4He/^3He$) sorption cooler developed by CEA/SBT [14] has been coupled by Air Liquide with a commercial Cryomech 4K PTC for precooling. This system [15] is the first cryogen free system able to provide 3 orders of magnitude in temperature. It provides ultimate temperature down to 265mK and typical cooling power of 20µW at 290mK. Hold time in excess of 2 days have been measured at temperature below 300mK. Drive electronic is under development and in a near future the complete system will be fully automated.

A similar approach has been used to associate an Air Liquide standard dilution fridge with a 4K PTC. This cryogen free system [15] provides more than 4 orders of magnitude in temperature with a continuous operation. An ultimate temperature of 8mK has been achieved with a cooling power of about 250 µW at 100 mK.

These SubKelvin commercial mechanical coolers are presented on Figure 4.

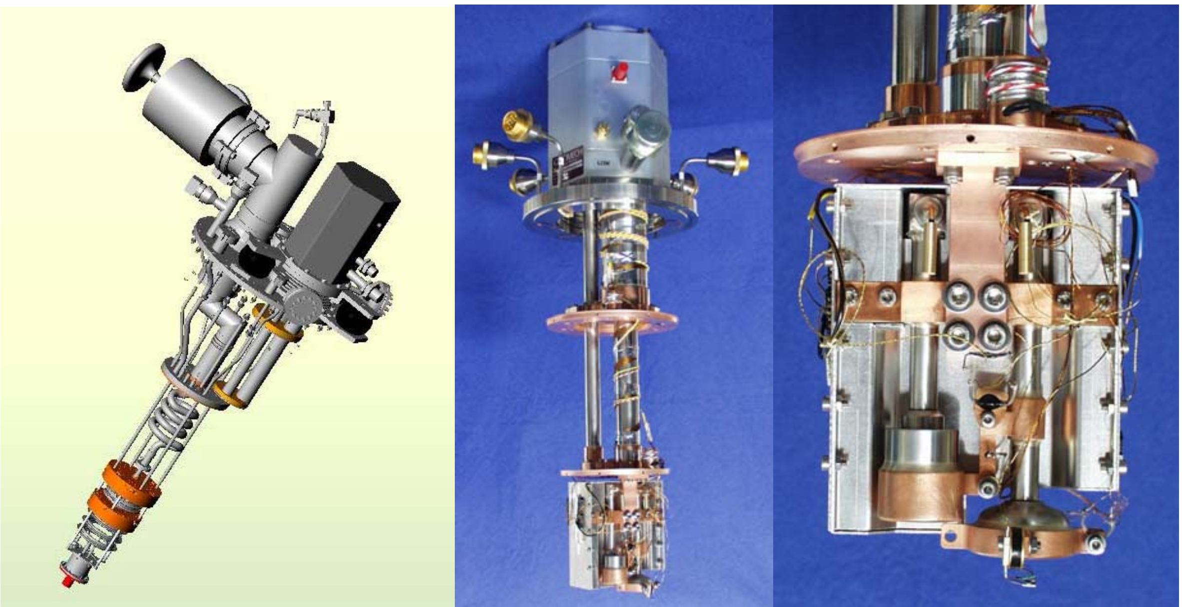

Figure 4: SubKelvin cryocoolers (4K PTC coupled with $^4He/^3He$ sorption or dilution stages)

Developments for space applications

Astrophysics missions in space requiring subKelvin cooling are already planed (Planck, Herschel) or foreseen in the future (Darwin).

Air Liquide has developed in partnership with CNRS/CRTBT and space qualified a dilution refrigerator for the cooling from 4 K down to 0,1 K in microgravity environment of the bolometers array of HFI (one of the Planck mission instruments). The CNRS/CRTBT has patented a unique design using 3He and 4He isotopes stored in high pressure vessels to feed a continuous mixing/separation process in a capillary pipe and rejecting the mixture (after a Joule Thomson expansion providing extra cooling at 1.6K) in space. This original process has been already demonstrated on ground against gravity (up side down cryostat) and in the Archeops stratospheric balloon mission. The qualification model has demonstrated the required cooling power of 100nW at 100mK [16] and has successfully survived the launching vibration tests.

CEA/SBT has developed and qualified a double stage ($^4He/^3He$) sorption cooler for two instruments (SPIRE and PACS) of Herschel mission. The technology of this cooler, including the gas heat switches required for cooler operation, has been extensively demonstrated on ground (operation against gravity) and in rocket missions. The qualification model has successfully passed the vibrations tests and demonstrated the specified performances: 10µW at 290mK, 2h recycling time and 46h hold time [17]. Flight models are under manufacturing.

Adiabatic Demagnetisation Refrigerators (ADR) are also candidates for subKelvin cooling in space or even in refrigerators for laboratory use. Few years ago, Cryogenic Spectrometers GmbH (CSP) has developed and coupled an ADR with a 4K PTC developed at Giessen University. A temperature of 60mK has been reached and 8 hours holding time at 100mK was provided. Under ESA contract, Oxford Instruments and Mullard Space are presently developing an ADR stage [18]. CEA/SBT has also undertaken such a development. Their specificity is to associate their ADR stage with an 3He sorption cooler: starting with precooling from 300mK will greatly decrease the magnetic field necessary to obtain an efficient demagnetization cycle [19].

An innovative superfluid vortex cooler (SVC) has been developed at Eindhoven TU [20]. SVC is a combination of a fountain pump and a vortex cooler. The working fluid in the SVC is superfluid ^4He. It is a small closed-cycle cooler with no moving parts. A certain amount of heat, supplied to the fountain part of the cooler, causes a circulation of helium in it. The total volume of the SVC is 1.25 cm^3. The cooler is gravity independent and requires little additional infrastructure. In principle a compact cryogen-free cooler with no moving parts in the cold area going down to temperatures below 1 K can be obtained. The PTR that achieves the required precooling temperature has been developed at the University of Giessen. It is a two-stage GM type PTR providing 8 mW of cooling power at 1.45 K. In the preliminary experiments with the integrated system a lowest temperature of 1.19 K has been reached.

CONCLUSION

New performances and reliability requirements for future HTS devices or space missions have simulated the development of new technologies. European academic institutions and industrial partners have initiated developments of different cryocooler technologies covering a large range of cooling power and cooling temperatures. Commercial products are already proposed by the industry and several demonstrators have demonstrated their performances and potential capability to be shortly industrialized. Challenging developments are also performed for future space missions.

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