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« TUBE PULSÉ »

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RECENT DEVELOPMENTS IN CRYOCOOLERS

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ABSTRACT

Cryocoolers based either on ideal Stirling and Ericsson or on irreversible Joule Thomson expansion cycles have been developed and are currently used for commercial applications (cryopumping, infra-red detectors cooling, cryostat thermal shielding). To extend their use to new applications (high transition temperature superconductors devices cooling, space-borne applications), technical improvements have recently been implemented which allow for higher reliability , larger cooling capacities and lower operating temperatures. An emerging technology, the pulse tube, has also been widely developed and could replace existing coolers in the near future.

1. INTRODUCTION

The boil-off in a cryostat of liquid cryogens (LN_2, LH_2 or LHe) generally produced by industrial processes has been the usual way to cool down and keep objects at low temperature.

Among the main industrial applications of cryogenic fluids we can point to the cooling at LHe of large superconducting magnets for particle accelerators or fusion tokomaks, LH_2 and LN_2 storage vessels for rocket cryogenic thrusters, ground freezing in civil engineering, the production of pure gas by liquid evaporation for either metallurgy or the semiconductor industry, etc.

Additional to these large cooling power applications for which remote or dedicated industrial liquefaction plants have been built (up to several tens of kW at LHe temperature), over several years, small scale mechanical autonomous cryocoolers with much lower cooling capacity (from a fraction of watt at LHe temperature to a few hundreds of watt at LN_2 temperature) have been developed, responding to specific cryogenic needs.

Low temperature has allowed physicists to discover fundamental phenomena which were hidden at room temperature by thermal agitation : superconductivity, helium superfluidity, non-ohmic resistivity in submicronic systems, magnetic ordering, quantized Hall effect ...

Technological applications of these properties have led to the development of new apparatus for detectors (IR detectors, high magnetic fields magnets, magnetic resonance imaging, bolometers for astrophysics, magnetometers, ...) which require cryogenic cooling.

The use of consumable cryogens for the cooling of such objects can be problematic : difficulties of replenishment of liquid supplies, perturbations during cryostat refilling, operation in all orientations or in zero-gravity, cost of operation. To overcome these inconvenience, mechanical autonomous cryocoolers have been developed and industrialised recent years. Among the major goals to be achieved for the commercial success of these new products are the reliability, the thermodynamic efficiency, the reduction in investment and maintenance costs, the increased lifetimes between failure, the control of induced perturbations (vibrations, electromagnetic noise, etc.) and the ease of system integration.

2. WHICH CYCLES FOR WHICH CRYOCOOLERS

Domestic refrigeration currently uses the Evans-Perkins compression cycle. The multistage or cascade (with several different cryogenic fluids) versions of this type of cycle are limited in the temperature range of natural gas liquefaction. To achieve cryogenic temperatures, other cycles are required such as Ericsson, Stirling or Joule Thomson isenthalpic expansion.

2.1 Reversible Process Cycles (Stirling and Ericsson)

The straight forward idea is to reproduce an ideal Carnot cycle (isentropic compression and expansion with isothermal heat exchanges at the cold and warm heat sinks). The required temperature difference between both cold and warm heat sinks in cryogenic applications would require very large and technologically unrealistic operation pressure : it is consequently impossible to conceive a Carnot type cooler using a fluid cycle (Carnot cycle can be followed in magnetic refrigeration).

Nevertheless it is possible to modify the Carnot cycle, as shown in figure 1 in a Temperature-Entropy diagram. For reversible transformations, the cooling power (represented by the dashed area below the isothermal transformation 1 → 2) and the mechanical energy involved (represented by the cycle area) remain unchanged. It is thus possible to define two new cycles characterised by isochoric (Stirling cycle) or by isobaric (Ericsson cycle) transformations instead of isentropic ones (Carnot cycle) and offering the same optimal theoretical thermodynamical efficiency. It is important to notice that contrary to isentropic transformations, isochoric and isobaric ones lead to heat transfers (area under evolutions 2 → 3 and 4 → 1). In the Temperature-Entropy diagram the isochors and isobars lines for a perfect gas are parallels (with respective slopes $1/C_v$ and $1/C_p$). Consequently the calorific energy to be provided to the cycle gas during evolution 2 → 3 is equal to the calorific energy to be extracted during evolution 4 → 1. It is thus possible to imagine a storage device which alternatively stores and rejects this energy during each cycle : the regenerator.

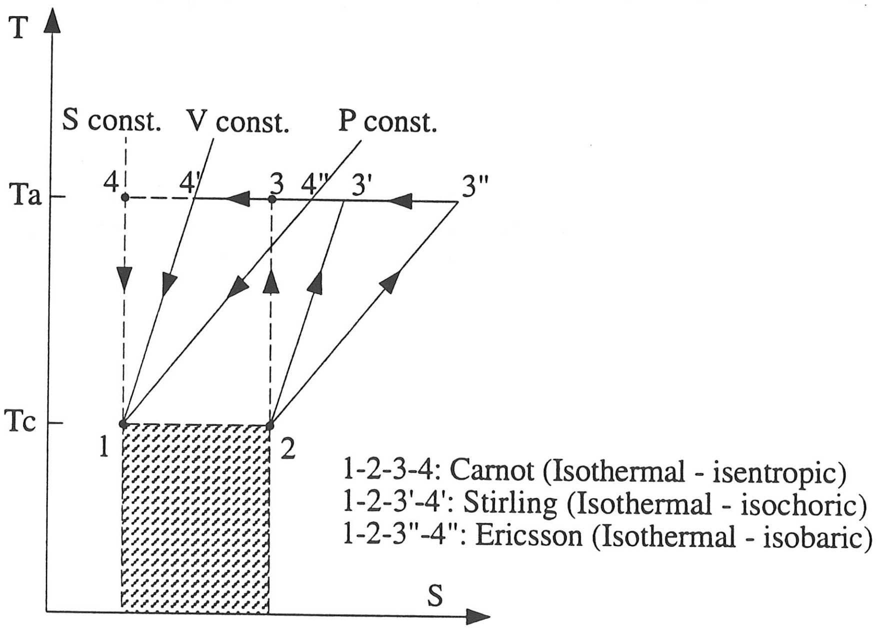


Figure 1 : Ideal cycles for cryorefrigerators

The regenerator is generally made of a porous material with a large heat capacity. It is subjected to the thermal gradient of the refrigerator (room temperature-cooling temperature). To reduce the parasitic conductive heat load under this temperature gradient, the regenerator is made of a stack of material which increases the overall thermal resistance by a large number of contact thermal resistances. In the temperature range 300 K – 80 K, metallic gauze discs (stainless steel or phosphorous bronze) are generally used (wire diameter and opening of the order of 30 to 100 µm). For two stage refrigerators in the temperature range 80 K – 10 K, lead shot (diameter of the order of 200 µm) is commonly used since this material exhibits a rather large heat capacity at low temperature.

At low temperature, the volume heat capacity of common regenerative materials decreases rapidly whereas that of helium, the unique potential cycle fluid remaining in the gaseous state in this temperature range, increases strongly. The regeneration is therefore inefficient : this is the reason why Stirling or Ericsson type cryorefrigerators are rather limited to operation above 10 K.

The practical operation of cryorefrigerators based on Stirling or Ericsson cycles leads to the use of moving parts (the gas expander/displacer and often the associated regenerator) in the cold finger to generate the appropriate cycle fluid volumetry and displacement.

2.2 Irreversible Process Cycle (Joule Thomson isenthalpic expansion)

The isenthalpic Joule Thomson (JT) expansion is a simple and static process which avoids any moving part in the cold finger of the cryocooler. An isenthalpic expansion can be obtained by a simple pressure drop through a calibrated orifice, a capillary or an adjustable needle valve. To obtain a cooling effect by such an expansion, the cycle gas has to be precooled at an appropriate level of temperature below the so-called inversion temperature (figure 2).

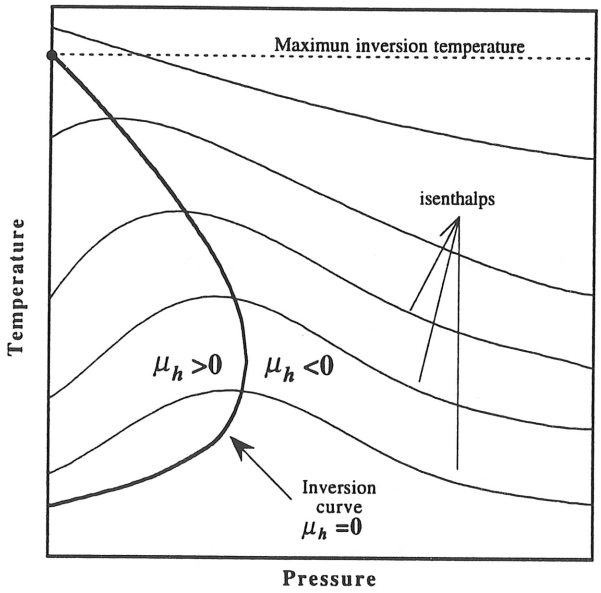


Figure 2 : Typical inversion temperature curve

This inversion temperature is reported for the main cryogenic fluids Table 1 with indication of the optimal high pressure range for the cooling effect during expansion :

Table 1 : Inversion temperature and optimal pressure for JT isenthalpic expansion cooling

Fluid	Inversion temperature (K)	Optimal pressure (MPa)
Nitrogen	621	20 – 60
Neon	260	20
Hydrogen	205	10 – 30
Helium	51	1.2 – 2.5

It can be observed that for nitrogen (or oxygen or air) no precooling below room temperature is required to obtain a cooling effect by isenthalpic expansion. But to achieve cooling by isenthalpic expansion of helium, the helium must be previously precooled below 50 K.

A typical JT cycle and its representation on a Temperature-Entropy diagram are shown in figure 3. In practice, the counterflow heat exchanger is sized to obtain a liquid vapour mixture after expansion. The cooling power is then produced by the latent heat of vaporisation of the liquid phase. The operation at liquid-vapour equilibrium allows a very good temperature stability of the cold sink (as long as the expansion pressure is well controlled).

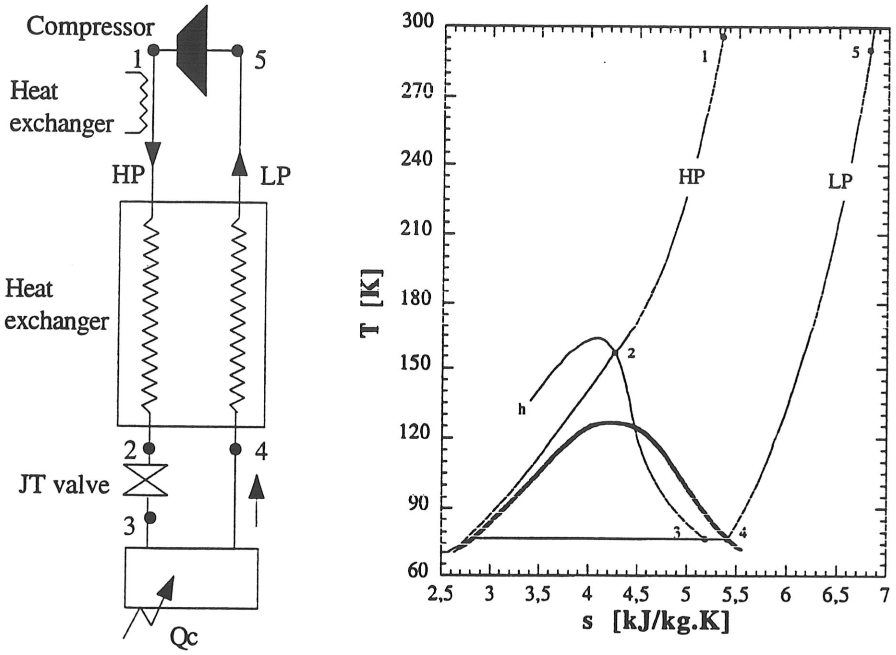


Figure 3 : JT expansion cooler cycle

The main theoretical drawback of the JT expansion is its irreversible nature which does not allow for an optimal thermodynamic efficiency. The main practical drawback of expansion devices (capillary or orifice) is potential plugging by solidification of impurities. Nevertheless J.T. coolers offer a simple and easily miniaturisable technology with no moving part in the cold region and have long been used in the Collins style helium liquefiers.

3. STATE OF THE ART – APPLICATIONS

3.1 Gifford Mac Mahon (GM) Cryorefrigerators

Cryorefrigerators operated with an Ericsson cycle are traditionally given the name of the engineers who first developed them in the US (Gifford and Mac Mahon).

The low (0.4 to 0.7 MPa) and high (1.5 to 2.5 MPa) pressures of the cycle are provided by a compression unit. Compressors manufactured for domestic refrigeration or air conditioning (piston type with crankshaft or rolling piston type) are modified to take into account the fact that the cycle gas, helium, is monoatomic ($\gamma = C_p/C_v = 1.67$) and consequently undergoes a large temperature increase under adiabatic compression. To limit this heating effect which is deleterous to the compressor life time (thermomechanical fatigue of the valves and cracking of lubrication oil), oil is injected in the compressor suction line to act as a thermal reservoir during compression. At the compressor outlet this oil is removed through three successive separation devices (centrifugation, coalescence with return line at LP and physical adsorption on an activated charcoal bed which requires maintenance by sorbant exchange every 10 to 30000 hours).

The compression unit is connected to a cold finger by flexible LP and HP lines. In the cold finger, a piston (displacer) including the regenerator is mechanically (crankshaft) or pneumatically driven, its displacement being synchronised (driven valve or rotating distributor) with HP gas inlet and LP gas outlet to reproduce the Ericsson cycle as shown in figure 4. These cryorefrigerators are generally operated at low frequency (a few Hertz).

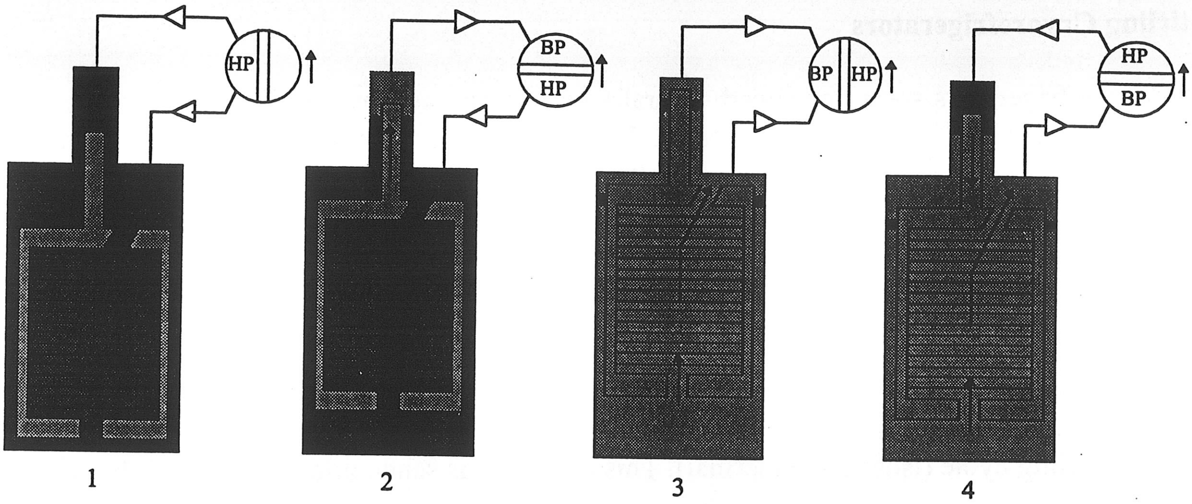


Figure 4 : Principle of operation of a GM cooler.

GM cryocoolers are widely commercialised. Their main area of application are :

- Cryopumping (figure 5).
- Cooling of thermal shields for LHe storage vessels or superconducting magnet cryostats.
- Cooling of dry HTc superconducting magnets.
- Precooling of mixed GM + JT cycles for liquid helium temperature coolers.
- Cooling of samples in cryostats for physicists.

Figure 5 : Cryopumps cooled with GM cold heads (courtesy of Edwards)

Several manufacturers are offering this type of cryorefrigerator (APD, CRYOMECH, CTI, CVI, EDWARDS, LEYBOLD, SUMITOMO, ...) in single stage (up to 200 W at 80 K) or double stage (up to 20 W at 20 K and simultaneously 80 W at 80 K) configurations with electrical power consumption of a few kilowatts.

3.2 Stirling Cryorefrigerators

Stirling cryorefrigerators were developed several tens of years ago by the Philips Company in the Netherlands for air and hydrogen liquefaction. These refrigerators with large cooling capacities (1 to 4 kW at 80 K and a few 100 W at 20 K) are still manufactured nowadays and could find new commercial opportunities in industrial applications of high transition temperature superconductors (electrical transformers, motors or current limiters). In recent years the development of Stirling cryocoolers has been largely driven by infrared detector cooling, mainly for military applications (night vision). Typical requirements are a fraction of, or a few watts in the temperature range 50 – 80 K. These coolers include a compressor (rotating driven by crankshaft or linear) which generates a pressure wave in a volume including a displacer and a regenerator. The motion of the displacer is controlled either mechanically or pneumatically in order to reproduce as well as possible the theoretical Stirling cycle (isochor-isothermal). This operation is schematically shown in figure 6.

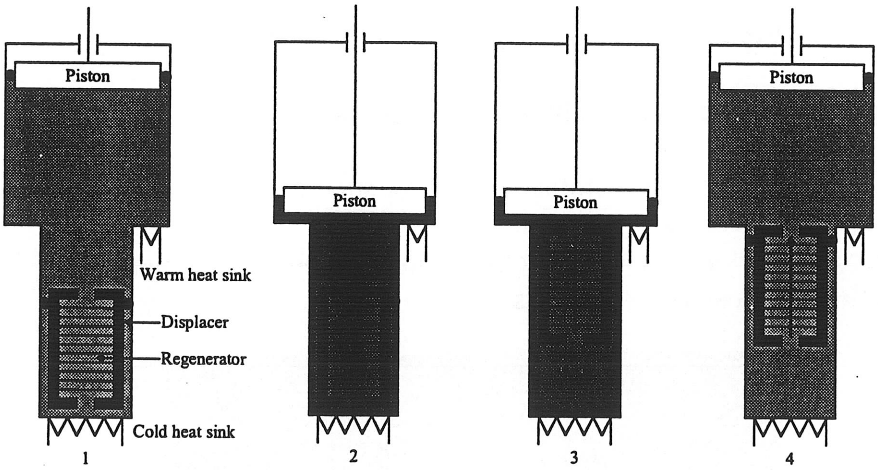


Figure 6 : Principle of operation of a Stirling cooler.

These cooler compressors do not require any valve. A pneumatic spring effect acts on the compressor piston due to the pressure difference between the back side of the piston at casing mean pressure and the front side in view of the oscillating cycle pressure. It results in an optimal resonance frequency (about a few tens of Hertz) near which such coolers are generally operated to reduce the electrical power input. Typically the lifetime between failure of these cryorefrigerators is about a few thousands of hours, mainly determined by sliding friction wear which leads to abrasion at compressor and/or displacer level. Typical electrical input power are of the order of 10 to 100 watts with specific consumption of 30 to 40 watt per output watt of cooling power at 80 K. Figure 7 shows industrial Stirling coolers, integral with rotating motor or split with linear motor, developed and commercialised for IR detectors cooling.

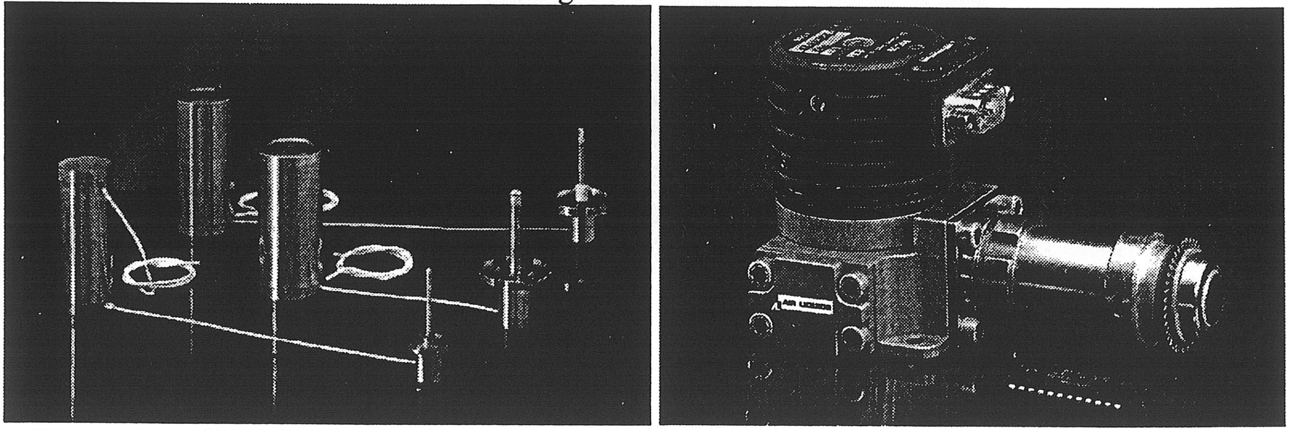


Figure 7 : split and integral Stirling coolers (courtesy of Cryotechnologies SA and Air Liquide)

3.3 Joule Thomson (JT) Cryorefrigerators

The main application of JT expansion cryorefrigerators is the cooling near liquid nitrogen temperature (80 K) of IR detectors for missile guidance. Required cooling power ranges from a few hundreds of milliwatt to a few watts for limited duration (a few minutes). Cryogenic fluids are commonly air, nitrogen or argon. These coolers are operated in open cycle configuration : gas is supplied from a high pressure storage bottle (20 to 60 MPa) and expanded at atmospheric pressure. Due to the high pressure of alimentation required to obtain an efficient operation, it is not feasible to imagine a closed cycle operation with a mechanical compressor, the cost of which would be prohibitive.

Figure 8 presents a schematic diagram of an open cycle JT cooler in its cryostat. The high pressure gas is precooled in a helicoidal finned tube heat exchanger wound around an insulating material mandrel and introduced in the cylindrical cryostat bore. The precooled high pressure gas after expansion is evacuated at atmosphere flowing in the annular space around the finned tube. Expansion occurs through a calibrated orifice, the open area of which can be adjusted if necessary by a conical needle the position of which can be controlled by a bulb type gas thermometer immersed in the expansion gas.

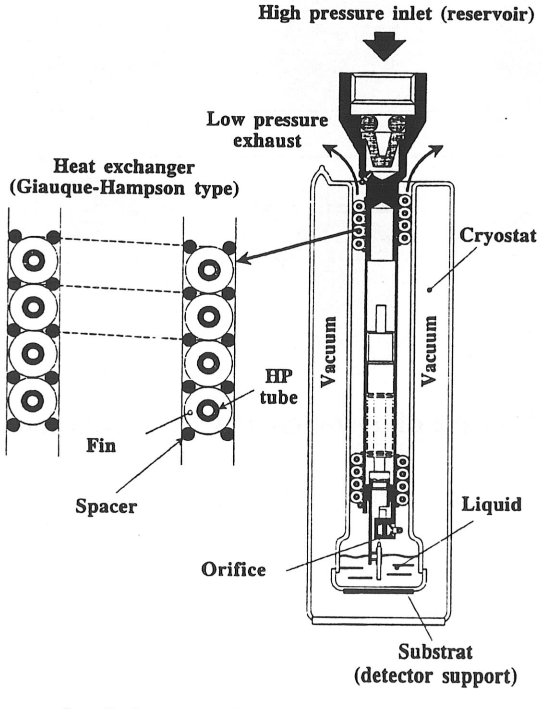


Figure 8 : Scheme of a JT cooler in its cryostat.

For sample cooling in laboratory applications, miniature JT systems have also been developed by the MMR company in the USA using microelectronics techniques for counterflow heat exchanger and expansion capillary etching in glass substrates.

4. NEW TRENDS FOR CRYOCOOLER DEVELOPMENTS

Cryorefrigerators are quite recent products. For specific applications (cryopumping, IR detectors cooling, MRI cryostat thermal shields cooling) their use is now common. To extend their range of applications (high critical temperature superconductors, helium liquefaction and/or recondensation, water vapour trapping), new developments are underway to improve reliability, to make system integration easier, to reduce their potential drawbacks (EMI, vibrations, ...) and to extend their cooling temperature range (single stage coolers down to below 50 K, multistage coolers down to liquid helium temperature).

4.1 Gifford Mac Mahon Coolers

These coolers although widely industrialised and commercialised are nevertheless undergoing continuous improvements.

4.1.1 Scroll type compressors. The recent adoption of scroll type compressors in the domestic refrigeration and air conditioning applications has been rapidly transferred to helium compression units used for GM coolers. The main advantages of this new technology are an higher efficiency, an improved reliability and acceptability for oil injection, a quieter operation. A schematic diagram of the operation of a scroll compressor is shown in figure 9.

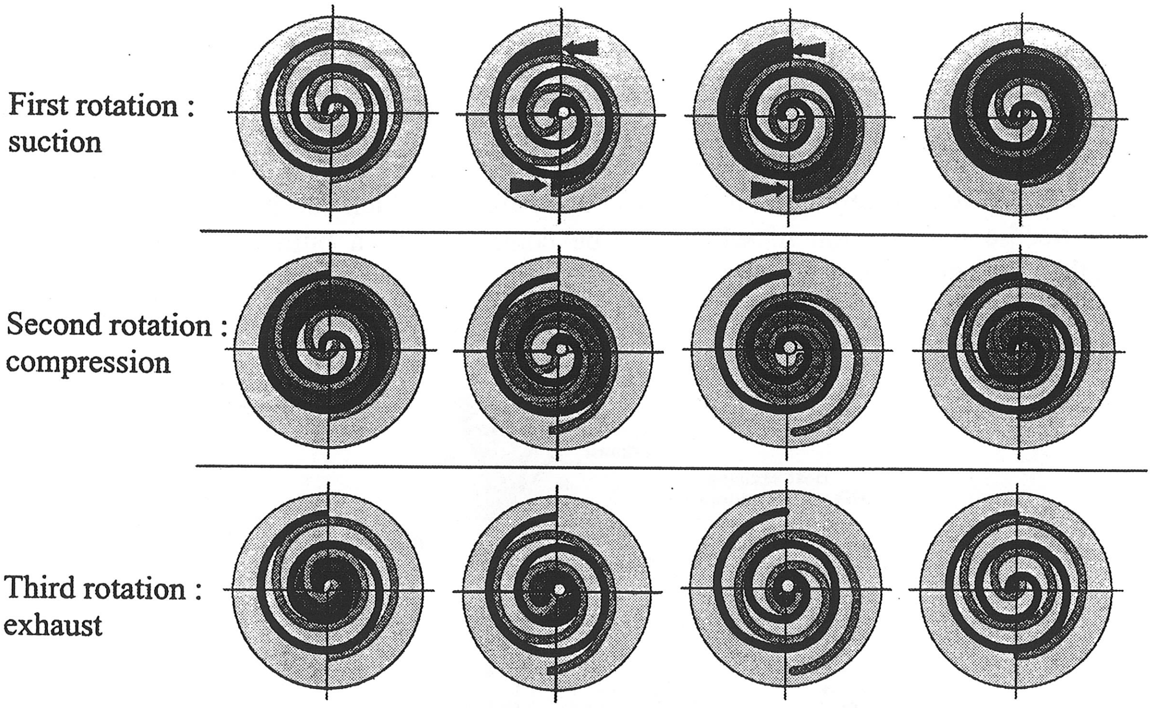


Figure 9 : Principle of operation of a scroll type compressor

4.1.2 Single stage GM coolers. Existing single stage GM coolers are generally sized and optimised to produce cooling power at LN_2 temperature (80 K). New potential applications (high transition temperature superconductor magnets or single thermal shield for helium cryostat cooling) are requiring tens of watts of cooling power in the temperature range 30 K – 60 K. To improve the performance of existing single stage GM coolers, the regenerator structure has been modified : lead shot (100-200 µm in diameter) is added to the conventional stack of stainless steel or phosphor bronze meshes. With such an arrangement, ultimate temperatures in the range 15 - 20 K are achieved with a significant cooling power in the range 30 K – 50 K. Experimental results have been published by LEYBOLD (1) with a 6 kW compression unit, the performances of this new generation of single stage GM cooler (15W/20K) being comparable with those obtained with conventional single and double stage GM coolers using the same compressor.

4.1.3 Two stage GM coolers. The goal assigned to future two stage GM coolers is a significant cooling power (from a fraction of, to a few watts) at liquid helium temperatures. The foreshadowed applications are detector cooling for astronomy and helium recondensation for superconducting magnet cryostats used in magnetic resonance imaging (MRI). For practical applications, these 4 K GM coolers should also provide sufficient cooling on the first stage at about 50 to 80 K for cryostat thermal shields cooling. The key technical point is the regenerator material which should have a large specific heat in the temperature range 10 K – 4 K to efficiently store the enthalpy transferred by the helium cycle gas. A proposed solution is to use magnetic materials which exhibit a magnetic ordering transition in the appropriate temperature range with a large associated specific heat anomaly. Several rare earth based materials have been characterised and tested for this purpose (2).

SUMITOMO for example is offering a two stage GM cooler based on this technology with simultaneously 1 watt at 4.2 K and 30 watts at 50 K of cooling power for an electrical input power of 7 kW. DAIKIN(3) and LEYBOLD(4) have published results of ongoing developments on similar systems. The main advantage of these new 4 K coolers is the quite simple and improved technology. The potential drawback is the presence of the magnetic material in the regenerator the brittleness of which may require specific conditioning (protective coating) to avoid long term degradation under the mechanical vibration generated by the alternate cyclic operation (about 1 Hz) of such coolers. This magnetic material may also be a constraint for MRI magnets or detector cooling due to their associated electromagnetic signature.

4.2. Stirling Coolers

4.2.1 Integrated dewar cooler assembly. Currently the main market for Stirling coolers is the cooling of infrared (IR) detectors for military night vision. A necessary requirement for this application is a higher level of integration of the detector-dewar-cooler assembly to reduce the temperature gradients and associated efficiency losses due to cumulative thermal barriers. This has been achieved by the development of the Integrated Dewar Cooler Assembly Concept in which the dewar bore wall is also the cold finger tube. The standard thermomechanical coupling at the cold tip between the cooler and the dewar is eliminated and the suppression of the cold finger tube reduces the heat load, allowing a given cooler to accommodate a larger detector and to be more efficient. The integral type Stirling cooler shown on figure 7 is of this type.

4.2.2 New civilian applications. High transition temperature superconductors are foreseen for the development of new electronic components. Filters for mobile phone reception stations are a potential application which would require an improvement of existing performances in terms of either life time (more than 5 years MTBF expected) or cooling capacity (5 W/60 K is a generally agreed specification). To improve the reliability of their Stirling coolers, manufacturers have developed linear driven pressure oscillators. The combination of specific coating on piston and/or cylinder and of a gas bearing effect associated with the clearance seal technology used for the piston/cylinder tightness (instead of traditional rubbing piston rings) have significantly reduced the sliding forces (in comparison with rotating motor compressors). MTBF up to a few tens of thousands hours are now close to being achieved. The development of twin linear piston compressors has also significantly reduced mechanically induced vibrations. Several Stirling cooler prototypes (5) featuring twin linear piston compressors have been recently developed to fulfil the future mobile phone station HT_c filters applications requirements. Figure 10 shows such a cooler.

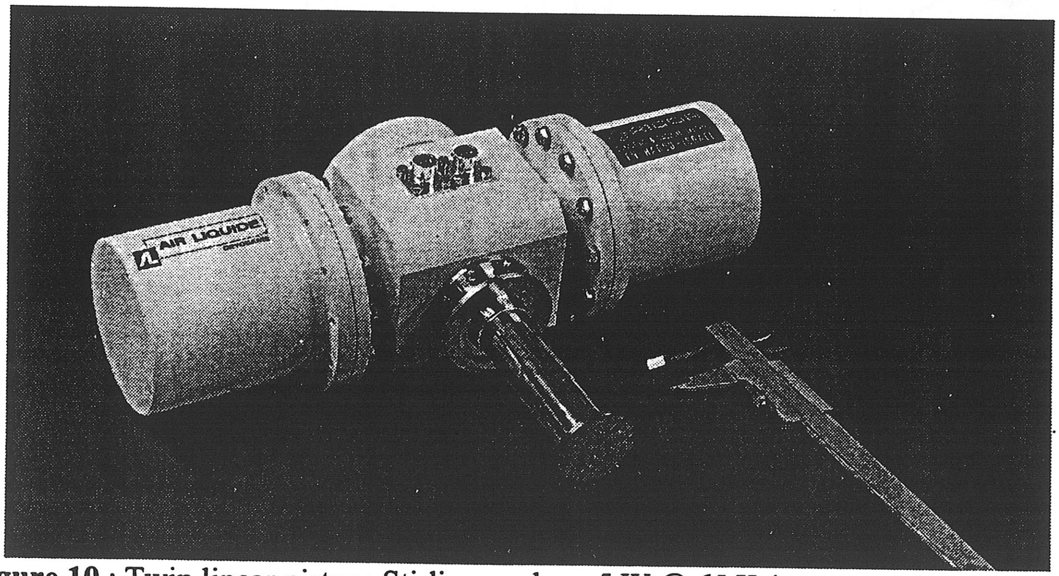


Figure 10 : Twin linear pistons Stirling cooler – 5 W @ 65 K (courtesy of Air Liquide)

4.2.3 Spaceborne applications. For spaceborne applications both a high thermodynamic efficiency and a high reliability are required. Today Stirling coolers allow for the highest specific cooling power and have therefore been selected. To improve the cooler reliability an original technology has been proposed and developed by Oxford researchers and has been adopted worldwide. The pressure oscillator piston and cold finger displacer are both suspended by flexure bearings which are characterised by a large radial stiffness allowing for clearance seal with no piston/cylinder contact. Coolers developed on this technology under European Space Agency funding have provided a high level of reliability (a demonstrator has been operated for more than five years without mechanical trouble). To obtain an optimal overall efficiency, both pressure oscillator pistons and cold displacer are driven by linear motors the stroke and phase of which are permanently controlled by means of position transducers. The electronic drive has also been adapted to adjust the command currents to obtain a good mechanical balancing of oscillator pistons (twin) in order to minimise exported vibrations which is often a strong requirement in spaceborne applications. Matra Marconi Space has developed a range of such Stirling coolers for space applications including single stage (2W/ 80K, 60W electrical input) and two stage (200mW/20K) models (6). A two stage Stirling cooler has also been utilized as a precooler to a closed JT expansion cycle using flexure bearings equipped compressors in order to achieve 4K.

4.3 Joule Thomson (JT) Systems

4.3.1 G.M. precooling. To operate a JT cooler at LHe temperatures, it is necessary to precool the cycle helium gas below 50 K before expansion. This precooling can be achieved by a two stage GM cooler. Moreover the JT loop helium mass flow rate, which generally represents a few percent of the GM cooler mass flow rate, can be by passed from the GM cooler compression unit : indeed, the optimal pressure for helium JT expansion is about 1.5 to 2.0 mbar, which exactly correspond to the high pressure of GM compressors. An additional low mass flow rate compressor is used to recompress helium after JT expansion (0.1 MPa or below) to the GM compressor suction pressure (0.6 to 0.9 MPa). The schematic diagram of a mixed GM + JT cooler is shown on figure 11.

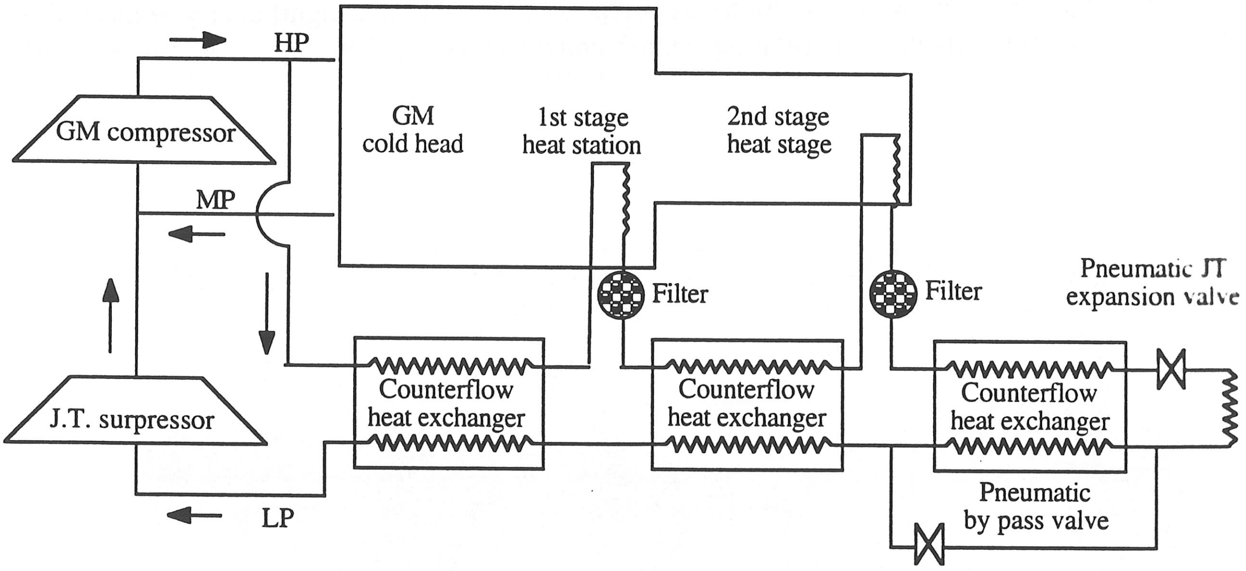


Figure 11 : Mixed GM – JT 4K cooler principle.

Such coolers have been developed in several laboratories (up to 5 W at 4 K) and even commercialised (APD, DAIKIN), mainly for helium recondensation in MRI cryostats, detector cooling (superconductor-insulator-superconductor (SIS) junctions for example) in astrophysics or laboratory purpose. One of the main problems encountered with these coolers is the plugging of the JT expansion device (a capillary or a calibrated orifice) or counterflow heat exchangers by impurities (water or hydrocarbons from compressor lubricating/cooling oil, hydrogen outgassing).

With the emergence of two stage GM using magnetic materials in regenerators, this technology of mixed GM + JT cycles will probably be abandoned, at least for low cooling power (< 1 W at 4 K).

4.3.2 Gas mixture expansion. In the range of temperature 80 K – 150 K, the use of air, nitrogen or argon in JT expansion coolers is restricted to open loop devices due to the high supply pressure required for efficient operation. It has been known for a long time (7) that the combination of hydrocarbons or chlorofluorocarbons with nitrogen (and even neon and hydrogen for lower temperature) is a way to overcome this problem. Multicomponent mixtures allow for larger cooling powers at intermediate temperatures (faster cooling) and especially lower supply pressure. It is therefore possible to operate a system in a closed loop configuration, using for compression a GM type compression unit. A commercial cooler based on this technology is proposed by APD (Cryotiger). This type of cooler is well adapted for operation in the 100 – 150 K temperature range where some industrial applications are identified such as cryogenic water trapping (in combination with a turbomolecular pump) or even cryosurgery. These coolers may also be adapted for HT_c superconductor cooling, their performance remaining limited in the temperature range below 70 K which is today the major goal for this application.

4.4 Pulse Tube

The new trends in cryocoolers previously described are mainly technical evolutions of existing systems. The pulse tube is a new concept.

4.4.1 History and principle. A schematic of a pulse tube is presented on figure 12. Basically all components of a classical regenerative cooler are present : a compressor with a distribution valve or a pressure oscillator to generate a cyclic pressure wave and a regenerator. The main feature is the lack of any displacer in the cold finger which consists of a simple hollow tube. The gas oscillating in this tube behaves like a gaseous piston. The performance of the pulse tube is mainly governed by the control of the phase of the movement of this gaseous piston.

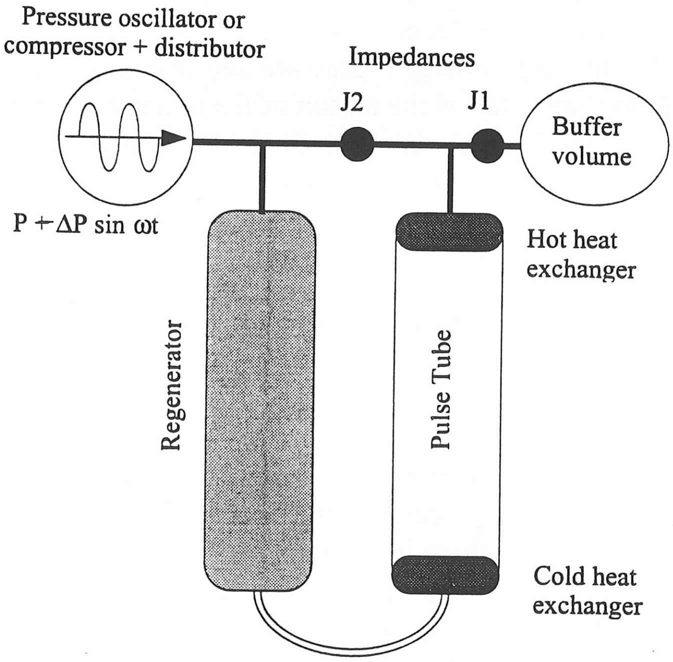


Figure 12 : Schematic of a Pulse Tube cooler

The first attempt to operate a pulse tube was by Gifford and Longsworth (8) with a closed tube. Performances were poor since no real phase control was performed and cooling effect was only due to a heat pumping effect along the tube wall limited in frequency and volume. Mikulin (9) first introduced an orifice and a buffer volume at the warm end of the tube, increasing significantly the performances. Radebaugh (10) proposed a phasor analysis of the pulse tube operation demonstrating that the role of the orifice and buffer was to control the phase shift between the pressure and gas mass flow oscillations of gas in the tube allowing to obtain maximal enthalpy flux between the cold and warm ends of this tube. Later Zhu (11) introduced the concept of a double inlet pulse tube, improving even more the performance by a reduction of the mass flow to be treated by the regenerator and contributing to control the phase shift. Based on these concepts and analysis, several developments have been initiated worldwide on this promising technology. The lack of a moving displacer in the cold finger guarantees potential advantages for the pulse tube : simplicity of manufacturing, drastic reduction of vibrations at the cold tip, ease of integration (no problem associated with mechanical effort eventually applied to the cold tip). The main drawback is a lower thermodynamical efficiency compared to Stirling or even GM coolers. Recent advances in pulse tube operation analysis are about to reduce this difference.

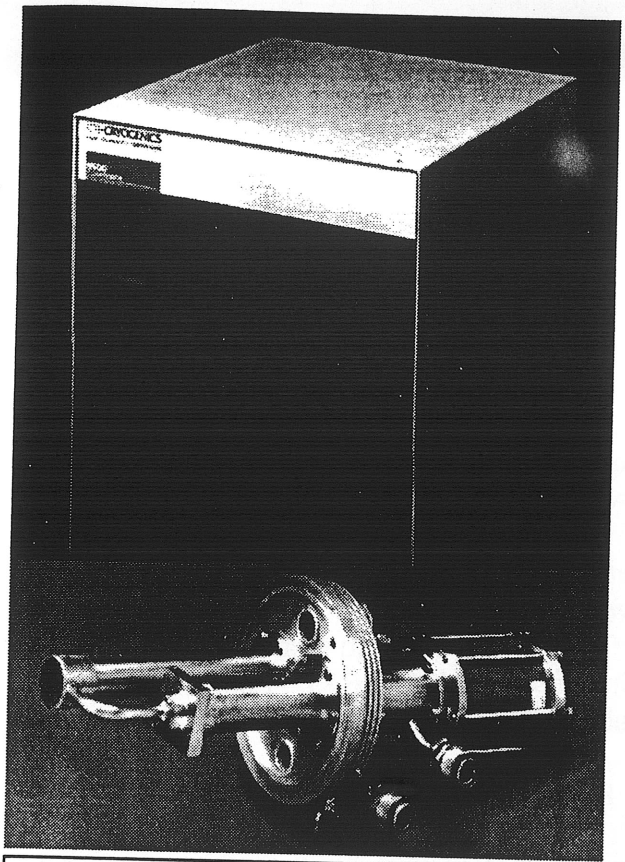
4.4.2 Recent advances : d.c. flow and inertance. The performance improvement demonstrated by the double inlet has encouraged most researchers to adopt this configuration. It has been predicted (12) and shown recently by indirect (13) observation (influence on performance) or by direct measurements of temperature gradients along the tube and regenerators (14) that this configuration is favourable to the establishment of a d.c flow in the regenerator and tube through the by-pass impedance. This is a parasitic phenomenon. The heat input at the cold end, even if the d.c. flow only represents a fraction of a percent of the oscillating main flow, can be of the order of the magnitude of the gross cooling. In pulse tubes operated in a GM like configuration (compressor + distribution valve) the addition of an adjustable needle valve between the buffer volume and the compressor allows for the introduction of a controlled d.c. flow which can compensate (and eliminate) the parasitic d.c. flow in the regenerator/tube subsystem. With this type of arrangement, double stage pulse tube coolers reaching liquid helium temperatures have been developed (15).

For pulse tube coolers operated in a Stirling mode at high frequency with a pressure oscillator, d.c. flow has also been observed and is more difficult to cancel. Fortunately, other considerations on phase shift control show that the double inlet configuration is not necessarily required.

Indeed, it is of major importance for pulse tube efficiency to have a control of the phase shift between the pressure and mass flow oscillations. For optimal operation, this phase shift should be zero. By analogy with electricity (16) (voltage = pressure and intensity = mass flow) an RC circuit can be used to adjust this phase shift : this is the reason of the impedance or orifice or valve (R) and buffer volume (C) at the warm end of the pulse tube. Such an arrangement allows for a phase shift control at the warm end of the tube but not necessarily at the cold tip where it is important to be adjusted. The only way to achieve this control would be to use the pneumatic analogy of an electrical selfinductance (L) to compensate for the tube volume (capacitance). Such a component exists : it is generally called inertance in acoustics. It is simply a tube (capillary) in which inertia effects produce the required phase shift. It is thus possible to obtain perfect control of the phase shift at the cold tip by use of the appropriate capillary (14) at the warm end between the tube and the buffer : this capillary play both the resistive (pressure drop) and selfinductance (inertance) roles. The by-pass line, the purpose of which is to contribute to the phase shift control, is no longer useful and consequently with its deletion the source for d.c. flow is suppressed. Of course the inertance effect is only efficient for high frequency operated pulse tubes (Stirling like) and not applicable for low frequency (GM type) systems. For these low frequency pulse tubes, various solution are under development in laboratories to obtain an appropriate control of the gas distribution to allow for an optimal phase shift at the cold tip. Among these suggestions we can highlight the four valve configuration (17) or the active buffer technology (18).

4.4.3 Pulse tube performances. As mentioned in the previous paragraph, the understanding of parasitic phenomena (d.c. flow) and phase shift control have led to significant improvements in pulse tube performances.

For space applications, high frequency pulse tubes have been developed (19) with specific consumption (30 to 20 W/W) comparable to Stirling coolers for cooling power of a few watts in the tempetrature range 50 – 80 K.



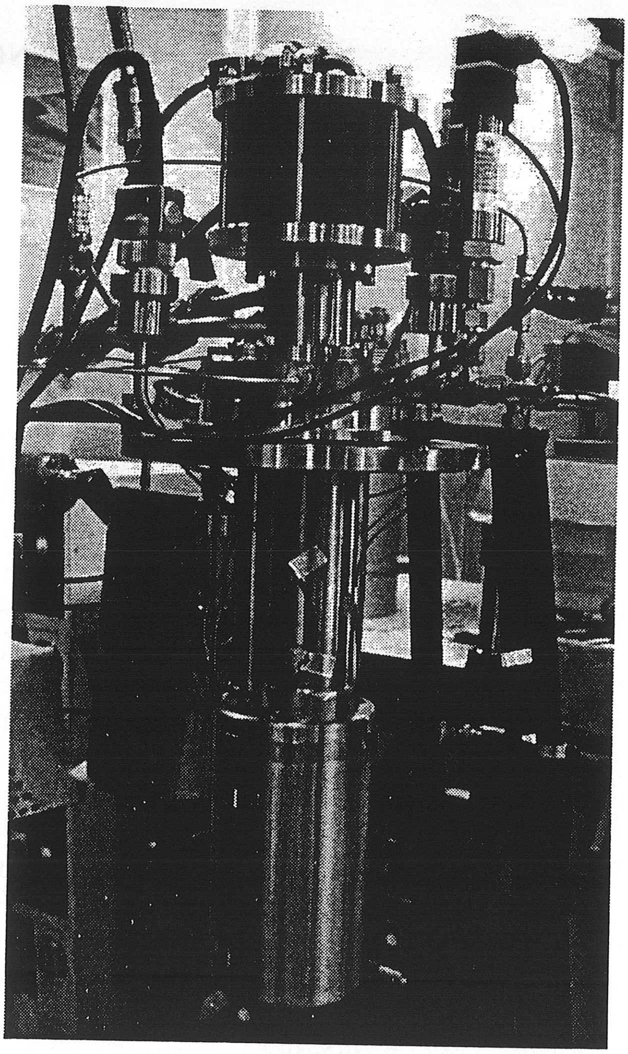


Figure 13 : Pulse tube prototypes CEA-SBT
Single stage 100 W@80K (above)
Two stages 15W@20K & 80W@75K

For ground-based applications several prototypes (see figure 13) of low frequency pulse tubes have been developed with cooling power comparable to GM coolers : single stage (100 – 160 W at 80 K (18,20)) and double stage with lead (10 W/15 K + 40 W/50 K (21)) or magnetic material (0.5 W/4.2 K (14)) regenerators.

The pulse tube is probably the most important recent evolution in cryocooler technology and is now mature for industrialisation.

5. CONCLUSION

Recent developments in cryocooler technology have significantly improved their reliability and field of potential applications. Larger cooling powers are now available and the range of ultimate temperatures has been substantially extended. Commercial mechanical coolers operating at liquid helium temperature are now available. The pulse tube technology has been around for a few years now and its maturity is such to be close to competing with Stirling coolers in terms of efficiency. This cooling technology provides a number of benefits among which are the ease of manufacture and system integration of cryocoolers.

As the number of cryocooler applications increases the production rate will also increase. The expected level at which cryocooler cost will be considered acceptable (1000 US dollars is a commonly required cost for reliable 5W/60K coolers) may be reached in the very near future.

REFERENCES

1. Fieldler A., Gerban J. and Haefner H.U., 1998, Efficient single stage Gifford Mac Mahon refrigerator operating at 20 K, *Adv. Cryo. Eng.*, CEC, vol. 43 : p. 1823-1829.
2. Hashimoto T., Nakane H., Tsukagoshi T. and Nakagome H., 1998, Recent progress in the application of magnetic regenerator materials, *Adv. Cryo. Eng.*, CEC, vol. 43 : p. 1541-1547.
3. Kurihara T., Okamoto M., Sakitani K., Torii H. and Morishita H., 1998, Numerical and experimental study of a 4 K modified solvay cycle cryocooler, *Adv. Cryo. Eng.*, CEC, vol. 43 : p. 1791-1798.
4. Lang A., Häfner H.U. and Heiden C., 1998, Systematic investigations of regenerators for 4.2 K refrigerators, *Adv. Cryo. Eng.,* CEC, vol. 43 : p. 1573-1580.
5. Workshop on Military and Commercial Applications for Low Cost Cryocoolers sponsored by the Electronic Industries Association in cooperation with DARPA, NRL and NVESD, 1998, San Diego, CA.
6. Jewell C., 1997, Overview of cryogenic developments in ESA, *Proceedings of the 6th European Symposium on Space Environmental Control Systems Noordwijk*, ESA SP-400 August 97
7. Alfeev V.N., Brodyansky V.M., Yagodin V.M., Nicholsky V.A. and Ivantsov A.V., 1971, Refrigerant for a cryogenic throttling unit, Patent Specification N° 1.336.892, London.
8. Gifford W.E. and Longsworth R.C., 1964, Pulse tube refrigeration, *Trans. ASME, J. Eng. Ind.,* vol. 86 : p. 264.
9. Mikulin E.I., Tarasov A.A. and Shkrebyonock M.P., 1984, Low temperature expansion pulse tubes, *Adv. Cryo. Eng.,* CEC, vol. 29 : p. 629.
10. Radebaugh R. and Storch P.J., 1988, Development and experimental test of an analytical model of the orifice pulse tube refrigerator, *Adv. Cryo. Eng.,* CEC, vol. 33 : p. 1191.
11. Zhu S., Wu P. and Chen Z., 1990, A single stage double inlet pulse tube refrigerator capable of reaching 42 K, *Proceedings 13th ICEC,* Beijing, p. 257.
12. Gedeon D., 1997, DC gas flows in Stirling and pulse tube cryocoolers, *Cryocoolers 9,* Plenum Press, New York, p. 385-392.
13. Chen G. and al., 1997, Modification test of staged pulse tube refrigerator for temperatures below 4 K, *Cryogenics,* vol. 37, no 9 : p. 529-532.
14. Duband L., Charles I., Ravex A. and Jewell C., 1998, Experimental results on inertance and permanent flow in pulse tube coolers, *Cryocoolers 10,* Plenum Press, New York, to be published
15. Wang C., Thummes G. and Heiden C., 1998, Performance study on a two stage 4 K pulse tube cooler, *Adv. Cryo. Eng.,* vol. 43 : p. 2055-2062.
16. Gardner D.L. and Sunft G.W., 1997, Use of inertance in orifice pulse tube refrigerators, 1997, *Cryogenics,* vol. 37, no 2 : p. 117-121.
17. Matsubara V., Tanida K., Gao J.L., Hiresaki Y. and Kaneko M., 1993, Four valve pulse tube refrigerator, *Proceedings of 4th Joint Sino-Japanese Seminar on Cryocoolers,* Beijing, p. 54-58.
18. Zhu S., Yakimi Y. and Matsubara Y., 1997, Investigation of active buffer pulse tube refrigerator, *Cryogenics,* vol. 37, no 8 : p. 461-471.
19. Burt W.W. and Chan C.K., 1997, New mid-size high efficiency pulse tube coolers, *Cryocoolers 9*, Plenum Press, New York, p. 173-182.
20. Ravex A., Poncet J.M., Charles I. and Bleuzé P., 1998, Development of low frequency pulse tube refrigerators, *Adv. Cryo. Eng.,* vol. 43 : p. 1957-1964.
21. Ravex A., 1999, Pulse tube coolers development at CEA/SBT, paper presented at the present IIF/IIR, Sydney Conference, to be published in the proceedings.

RECENTS DEVELOPPEMENTS DES CRYOREFRIGERATEURS

RÉSUMÉ: Des cryoréfrigérateurs fonctionnant suivant les cycles ideaux de Stirling et d'Ericsson ou suivant le cycle irreversible de Joule Thomson ont été développés et sont couramment utilisés dans des applications commerciales (cryopompes, refroidissement de détecteurs infrarouges, ecrantage thermique de cryostats). Pour elargir leur domaine d'application (refroidissement de systèmes mettant en jeu des matériaux supraconducteurs à haute temperature de transition, applications spatiales), des améliorations techniques ont été recemment mises en œuvre pour augmenter leur fiabilité, accroitre les puissances frigorifiques et abaisser les temperatures de refroidissement. Une nouvelle technologie émergeante, le tube à gaz pulsé, a également fait l'objet de nombreux développements et pourrait remplacer les machines existantes dans un proche avenir.

20W/lv @80K.

~100W@70K /5kW el.

Tmin=20K.

30W@30K. Tmin=17K.

⚠ quanti si BF > 7Hz ou pour la position