SORPTION COOLERS DEVELOPMENT AT CEA-SBT

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ABSTRACT

The reliability requirement associated with the development of cryocoolers for space applications leads to the rule that a reliable cooler shall be simple, have no friction or better have no moving parts. CEA-SBT has acquired a large experience on both aspects and we present in this paper our past and current cryogenic sorption coolers activities.
Adsorption coolers rely on the capability of porous materials to adsorb or release a gas when cyclically cooled or heated. Using this physical process one can design a compressor/pump which by managing the gas pressure in a closed system, can condense liquid at some appropriate location and then perform an evaporative pumping on the liquid bath to reduce its temperature.
These self-contained coolers require only electrical connections and thermal contact in order to operate from a cold heat sink. During ground testing they can be recycled in a wide range of orientations. Moreover the absence of moving parts makes them reliable and vibration free. They can be recycled indefinitely with over 95% duty cycle efficiency using simple control electronics.
we have developed several adsorption ^{3}He and ^{4}He coolers with specific design for zero-g operation. These coolers achieve sub-Kelvin temperature with autonomies ranging from 1 day to 2 weeks for typical net cooling power ranging from 10 to few hundred of micro-watts. In addition under an ESA contract, we have designed and space qualified a gas thermal switch suited for the cyclic operation of this type of adsorption cooler. This thermal switch is also based on physisorption principle.
Several project currently on going at CEA-SBT are presented.
Indeed these cooling techniques have potential applications in the growing number of missions that rely on detectors cooled to sub-Kelvin temperatures.

1. INTRODUCTION

Adsorption is the physical mechanism upon which a gas can be trapped onto a material surface : if a gas is brought into contact with a solid surface, some of the molecules striking the surface will be retained for a finite period of time, resulting in a significantly higher molecular concentration at the surface than in the gas phase. Depending on the magnitude and nature of the attractive forces the effect is described as chemisorption or physisorption. In the first case a chemical bond is formed and the process involves a transfer of electric charges. Physisorption, scope of the present work, relies on the relatively weak van der Walls forces. Evidently material with high specific area, such as activated charcoal (up to 1200 m^2 per grams) are required. The amount of gas adsorbed is then a strong function of pressure and temperature; it increases as the temperature decreases and the pressure increases.
Thus by varying the temperature it is possible to provide either a compression or a pumping effect. The former can be used for instance to drive a Joule Thomson loop, the latter can be used to perform an evaporative pumping on a liquid bath and thus reduce its temperature. In addition physisorption, or the ability to vary the pressure by varying the temperature, can also be used to design very efficient gas gap heat switches as shown further.

We will focus in this paper on the helium evaporative sorption coolers. It should be noted that CEA-SBT has also done some developments on the compressor aspects: two Joule Thomson cryocoolers capable of reaching respectively liquid helium and liquid nitrogen temperature were studied, which distinctive feature was the use of adsorption cryogenic thermal compressors (Refs. 1, 2).
Helium sorption refrigerators have no moving parts, are vibrationless and can be designed to be self contained and compact with a high duty cycle efficiency. These features and the expected reliability that follows make them very attractive for space applications. In addition the thermal and mechanical interfaces are fairly simple. The links to ambiant temperature are limited to the heater wires used to drive the sorption pump and the heat switches. It should be noted that this type of cooler is the last stage of a cooling system. It requires a pre-cooling stage at a temperature lower than the helium liquid-vapor transition ($\leq$ 3 K for ^{3}He and $\leq$ 5 K for ^{4}He), with enough cooling power. This can either be a helium bath (typical for laboratory units, or on payload like FIRST), or a mechanical cooler (for instance a ^{3}He Joule Thomson cooler - see further). Concerning the drawbacks relatively poor thermodynamic efficiency with regards to Carnot due to the heat of adsorption, and one shot operations can be noted.
The above features associated with recent advances in detectors technologies (see for instance Ref. 3) have boosted the interest for these cooling techniques. In the last two years only CEA-SBT has delivered about 10 laboratory ^{3}He units to various customers, and is involved in some new developments and space based projects.

2 SORPTION COOLER TECHNOLOGY BACKGROUND EXPERIENCE

The principle of operation of a sorption cooler has been described in numerous paper and the reader is referred to the relevant publications (see for example Ref. 4). Fig. 1 shows a schematic of what could be a general layout for a sorption cooler. In this figure all options are considered: ^{3}He, ^{4}He, laboratory or space use.
For a ^{3}He system in a laboratory configuration gravity is used to move the liquid from the condenser to the evaporator and to confine this liquid to the evaporator. In this case no heat switches are required; note that the heat switch on the sorption pump can be replaced for all configurations by a passive thermal link but at the cost of some additional power on the main cold plate. The design and operation of a ^{4}He system is slightly different mostly because of the superfluid ^{4}He film which creeps up the wall of the pump tube and dramatically degrades the performance. To reduce this effect a small diaphragm can be installed in the pumping line. However this solution prevents the liquid to fall by gravity during the condensation phase from the condensation point into the

evaporator, and thus does require the use of a heat switch to condense the liquid directly in the evaporator.

For operation in a zero-gravity environment liquid is condensed directly into the evaporator by establishing the necessary temperature gradients using a heat switch, and hold there by capillary attraction inside some porous material. Both the surface tension and the vapour pressure provide forces that drive and hold the liquid at the coldest point.

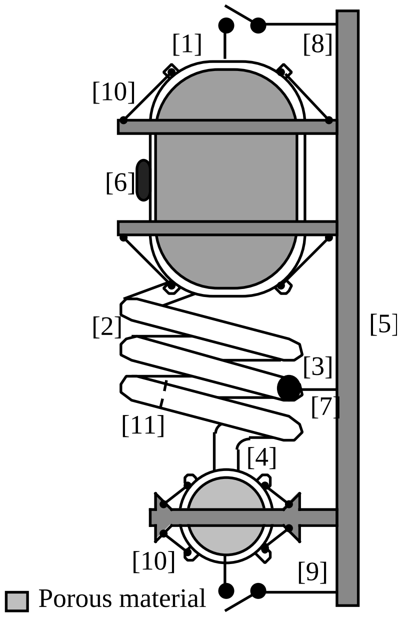

Figure 1 : General layout for a sorption cooler
^{3}He laboratory version : [1]: sorption pump, [2]: pump tube, [3]: condenser, [4]: evaporator, [5]: cold stage, [6]: heater, [7]: thermal link, [8]: heat switch, [10]: support structure
^{4}He laboratory and space version (both): idem, except [3] suppressed, [4] Condenser/Evaporator, [9]: heat switch and [11]: diaphragm (only for ^{4}He)

Like any other coolers a number of specifications are required for the design of a sorption cooler. In order to get a better understanding on the sizing three main requirements can be briefly discussed, the ultimate temperature, the hold time and the average power dissipated on the main cold stage. These three parameters are somewhat linked. The following discussion only applies to self contained ^{3}He unit.
In a well designed cooler the ultimate temperature is only limited by the pumping line between the sorption pump and the evaporator, i.e. the length, diameter and wall thickness of the tubes. Generally this temperature will lie between 260 and 300 mK. Lower temperature are extremely difficult to obtain since in this range to lower the temperature by 10% requires to lower the pressure P above the bath by about a factor of 4. If we assume that the applied thermal load on the evaporator (detectors, etc...) is negligible in comparison with the parasitic load (heat conduction along pumping line) one can easily show that as a first approximation the pressure P is inversely proportional to the tube diameter Ø. If the applied load is taken into account the diameter must be further increased.
But again neglecting the applied load and within a limited range for the tube length L (see further), the hold time can be shown to be proportional to the amount of gas, the tube length L and inversely proportional to the square of the pump tube diameter. It could be set to any value by matching the above parameters. Yet there is obviously a balance to be found with the ultimate temperature.

The alternative is then to compensate these conflicting aspects by adjusting the tube length and amount of gas. However although not as simple, the ratio between the amount of gas and the hold time (thus roughly proportional to $Ø^2/L$) provides some indications on the average power dissipated on the cold plate over one cycle, which in most case is required to be as small as possible.
Finally the condensation efficiency and consequently the hold time can be substantially degraded by an increase of the internal volume of the pumping line ($\approx L.Ø^2$). In fact for a given cooler without any applied load detailed calculations show that the ultimate temperature indeed does not depend on L, but that for large length the hold time is not anymore proportional to L and eventually decreases as L increases.
The bottom line is that the ultimate temperature, hold time and average power dissipated cannot be simultaneously optimised and a compromise has to be found. Nevertheless these coolers can be customised and made to any size.

We have designed or contributed to the design of a number of helium sorption coolers for laboratory and space use, a few examples of which are shown on the following pictures. Two rocket-borne coolers (one ^{4}He and one ^{3}He), as well as a space-borne ^{3}He system have been successfully flown and have provided the first Sub-Kelvin temperature in zero-G (Refs 5, 6, 7, 8, 9)

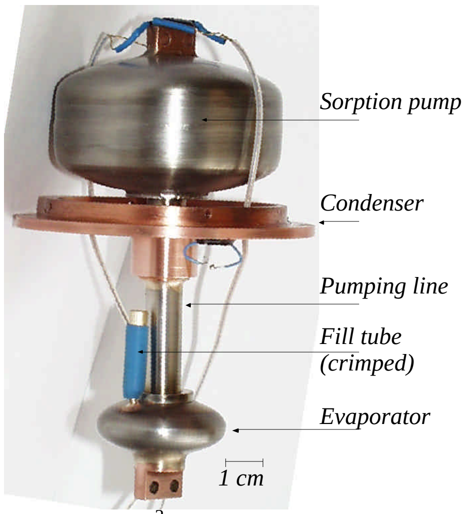

Figure 2 : Laboratory ^{3}He sorption cooler (4 liters STP unit)

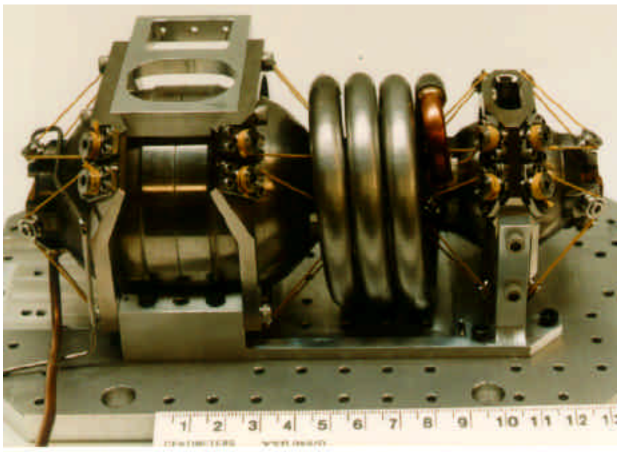

Figure 3 : Orbital ^{3}He cooler successfully operated in orbit in April 1995 on board the Infrared Telescope in Space

Operation of the space sorption coolers would not be possible without efficient heat switches. Cryogenic heat switches based upon different physical mechanisms can be used. In the framework of an ESA contract various techniques were evaluated and gas gap switches were considered more advantageous. This type of switch utilises concentric copper cylinders separated by a small gap which is filled with or emptied of ^{4}He gas to achieve the switching action. The thermal separation between the two ends is achieved by a thin-walled stainless steel tube which also provides the mechanical support. The presence or absence of gas is controlled by a miniature cryogenic adsorption pump that can be temperature regulated. A complete description of these switches is given in Ref. 10.

3 NEW DEVELOPMENTS AND PROJECTS

Several projects are currently on going at CEA-SBT. As of today all helium adsorption coolers that have been developed for space applications were operated from a pumped ^{4}He bath. Indeed for specific applications this technology would benefit if the helium tank could be replaced by a system that would only required input power for its operation and would provide long life operation. In this framework a feasibility study on a three stages cooler has been performed. This study funded by ESA is carried out by a coordinated team lead by MMS Bristol supported by the Rutherford Appleton Laboratory (RAL) and the Service des Basses Températures of CEA-Grenoble (SBT). CEA-SBT is responsible for the 0.3 K stage study and design (Ref. 11).
RAL has extended the technology based on the split single stage 50-80K Stirling cycle cooler of the Oxford/RAL type design [Ref. 12, 13], to a two stage system to which has been added a Joule Thomson loop. The latest performance show that the cooling power and ultimate temperature are now compatible with the operation of an adsorption ^{3}He cooler. This ^{3}He sorption cooler will thus enable temperatures down to 0.3K to be reached without the need for an ^{4}He tank.

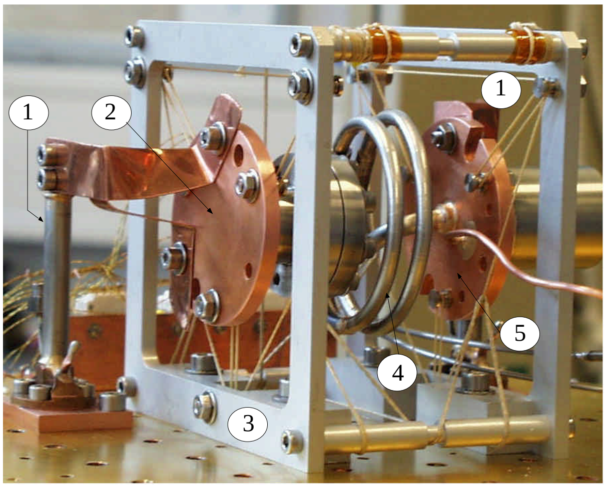

Figure 4 : 0.3 K prototype stage of the 300 K - 0.3 K mechanical cooler, mounted in the test cryostat [1] : heat switch, [2] : evaporator/condenser, [3] : laboratory support structure, [4] : pumping line, [5] : sorption pump,

A two liters STP unit has been studied and presized assuming a maximum available cooling power for the sorption cooler of 3 milliWatts at 2.5 K. This requirement represents certainly the most severe specification and call for a precise knowledge and control of all energies and power involved in the cycle. The thermodynamical analysis of the cooler has been refined and our model has been improved to assess these aspects. In addition when the ^{3}He cooler will be integrated onto the mechanical cooler a specific thermal architecture will be used.
The first prototype has been assembled and preliminary experimental tests have been carried out using a standard ^{4}He cryostat and gas gap heat switches. A picture of the first prototype is shown in Figure 4.
A support structure using Vectran wires is used. This new material is presently being characterised but the preliminary results seem to indicate its performance are fairly similar to Kevlar but with less creep, an additional resistance to abrasion and a better strength in the transverse directions (to be published).

In figure 5 successful operation of this cooler against gravity is demonstrated. In addition the measured cooling power curve is consistent with prediction. It should be indicated that this cooler is not designed to provide very low temperature, but to operate from 2.5 K with little power available. This prototype will be integrated on the mechanical cooler shortly.

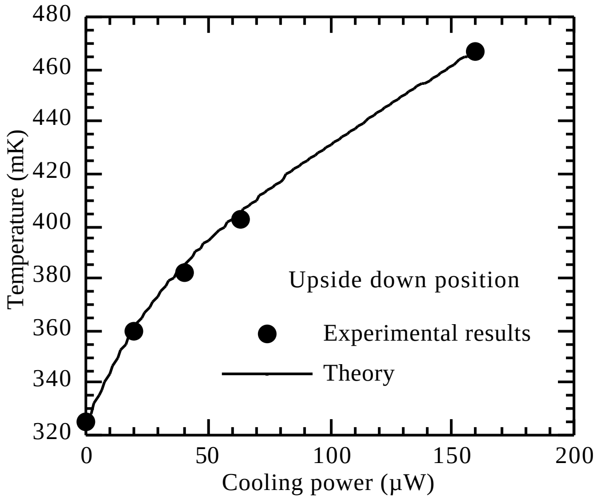

Figure 5 : Cooling power curve for the 0.3 K stage Measurements performed against gravity

If this project is brought to a successful conclusion this cooler will be the first liquid cryogen bath free able to provide 3 orders in magnitude in temperature from 300 K down to 300 mK.

Although we have acquired a large experience in sorption coolers technology, most of the work performed for space purpose was done at laboratory level basically on a single prototype basis. Hence this year ESA issued a competitive request for quotation (RFQ) to bring the existing technology of the sorption cooler to a level compatible with space missions. This RFQ was won by a collaboration composed of CEA-SBT and Centre Spatial de Lièges (CSL).

In addition CEA-SBT will be responsible for the development and space qualification of the sorption cooler for the SPIRE instrument onboard the FIRST satellite. The above ESA contract will certainly benefit these developments and provide additional design tools and know-how.

The cooling of the SPIRE detector arrays to 300 mK will be effected by a ^{3}He sorption cooler similar in design to the one successfully flown on the IRTS mission in April 1995 (see figure 3). The base-line SPIRE cooler contains 4 STP liters of

^{3}He, fits in a box 200 x 100 x100 mm and weighs about 500 grams. Operated from a 1.8 K heat sink it should achieve for instance a temperature of 274 mK with a 8 microwatts load on the evaporator, a lifetime of 46 hours and a duty cycle efficiency of 96%. The total time averaged power dissipation per cycle to the 1.8 K heat sink is expected to be 2.4 mW.

4. CONCLUSION

Sorption technology offers attractive features for space applications in the Sub-Kelvin temperature range. Among the current technologies, adiabatic demagnetisation or dilution refrigerator, it is certainly the simplest in terms of interface and operations, and has the smallest mass and volume. Although a number of helium sorption coolers have been flown, this techniques require some additional efforts to be brought to a level compatible with general space missions. CEA-SBT who masters this know-how has recently been awarded an ESA contract for this purpose. In addition CEA-SBT will be responsible for the SPIRE ^{3}He cooler onboard the FIRST satellite.

Indeed this cooling technology should acquire its full maturity in the coming years.

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