Development of the Closed-Cycle Dilution Refrigerator for Space Applications

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ABSTRACT

We present the development of the closed-cycle dilution refrigerator (CCDR) derived from the open-cycle dilution refrigerator (OCDR) used in the Planck mission. Unlike the OCDR, the two isotopes ^4He and ^3He are circulated (with a fountain pump for the ^4He and with a compressor for ^3He) instead of rejecting to space in order to increase the lifetime of the system. Each individual block is working and the full system is under development.

In this work, we discuss the development of the different parts of the CCDR and the next steps to be performed in order to achieve the cryogenic performance for a future mission (1μW at 50mK). We address more specifically the ^3He compressor options and the status of one solution identified as the Holweck compressor. Then, we propose a possible integration according to constraints of the future space missions.

INTRODUCTION

The gravity insensitive open cycle dilution fridge (OCDR) was developed for use in the Cosmic Microwave Background (CMB) of the Planck mission. The main breakthrough of this system consists of mixing ^3He and ^4He due to its capillaries forces and not to gravity as in a standard dilution refrigerator. In the OCDR, the two isotopes were injected from two separate reservoirs into the mixing chamber and then they were ejected into space. The OCDR provides 0.1μW at 100 mK for 2.5 years with a continuous flow of 5.4 μmol/s of ^3He and of 14.5 μmol/s of ^4He[1].

The current mission projects (ATHENA+/X-IFU, COrE, Prism) need a greater cooling power (1 μW at 50 mK) for a longer time, typically 5 years. It is not realistic to use OCDR as a possible sub-Kelvin cooler because of the quantity of isotopes needed for this mission. Hence, the cycle must be closed. In a promising development, a gravity insensitive Closed Cycle Dilution Refrigerator (CCDR) has already reached a performance of 1 μW at 51 mK [2,3].

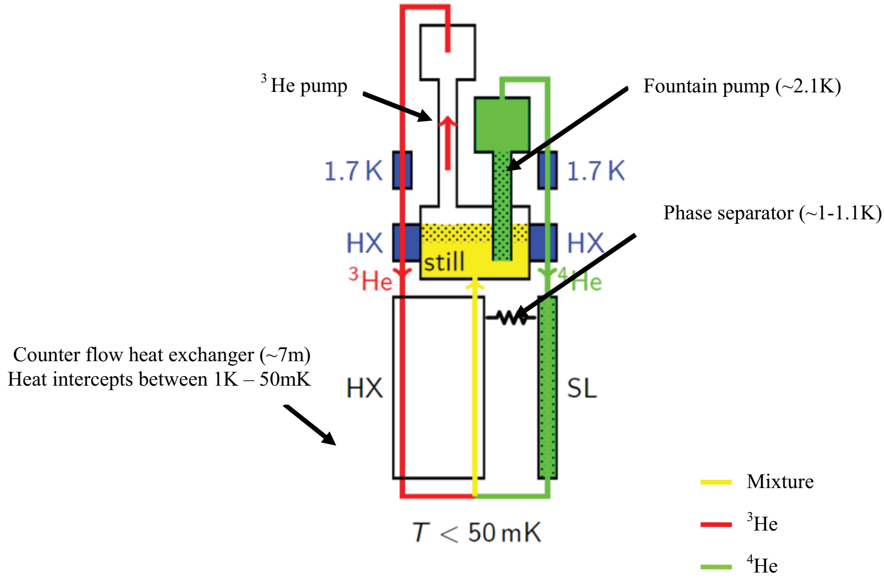

Figure 1. Schematic view of the CCDR.

THE CLOSED-CYCLE DILUTION REFRIGERATOR

Figure 1 shows the CCDR. The key principle is to inject the two helium isotopes through two separate capillaries and mix them in a third one. The Y junction between the three capillaries is the equivalent to a "mixture chamber" in a standard dilution fridge. At temperature below 100 mK, the solubility of ^{3}He in the dilute is limited to 6.6%. If the quantity of ^{3}He exceeds this value, not all ^{3}He is diluted but some stays in concentrated phase to form droplets that fill the cross section of the capillaries where capillary forces play the role of gravity.

The liquid mixture produced in the mixture chamber goes into the counter flow heat exchanger to pre cool the ^{3}He and the ^{4}He returning from the still. Then, it enters the still where the two isotopes are separated. The superfluid ^{4}He is extracted with a fountain pump which can only extract superfluid ^{4}He so it has to work below the lambda point of ^{4}He (2.17K). The ^{3}He is extracted by pumping the rich gaseous phase with a pump working at much higher temperature (15K or 300K). The almost pure ^{3}He (~95%) is then re-condensed into the CCDR. In order to work under zero gravity, the liquid vapor phase separation has to be realized into a porous materiel to confine the liquid. This porous material can be made of Procelit 160 that has a porosity of about 90% and has been used in ^{3}He sorption cooler for space application[4]. The ^{3}He pressure in the still shall be in the range 5-10 mbar in order not to affect the cooling performance as shown in Figure 2.

The cooling power is dominated by the ^{4}He flow rate rather than ^{3}He flow rate since all ^{4}He goes into the dilute phase while only a fraction of ^{3}He is diluted. The ^{3}He flow rate needed is 18.1 µmol/s, as compared to the 350 µmol/s for the ^{4}He.

Along the counter flow heat exchanger from 1 K to 50 mK, a continuous cooling power can be provided to electrical wires, and the mechanical support without affecting the cold tip temperature.

A heat sink at 1.7 K is needed to reduce the heat load on the still and to re-condense ^{3}He. In the situation described above, a cooling power of about 5 mW is needed at 1.7K.

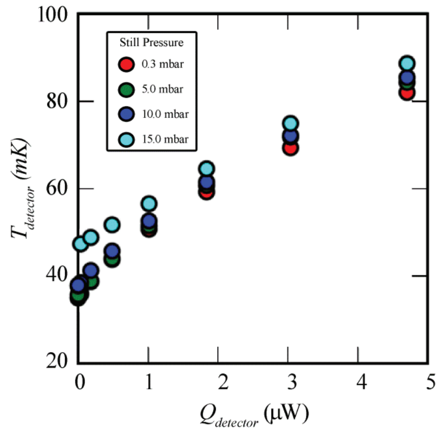

Figure 2. Temperature of a detector simulator versus the heat applied to the simulator for a still pressure of 0.3 (red), 5 (green), 10 (blue), and 15 mbar (cyan).

^{3}HE PUMP SOLUTIONS

To achieve a cooling power of 1 μW at 50 mK, the ^{3}He flow rate needs to be around 20 μmol/s (corresponding to 0.7L/s at 300K) with an inlet pressure of 5 mbar and an outlet pressure of 200mbar. There is currently no space qualified compressor that satisfies those requirements. Three solutions are under investigation:

- A system based on existing space linear compressors developed by JAXA-SHI for a 1K-class JT cooler in the frame of the SPICA mission[5].
- A cryogenic sorption compressor operating at 15 K developed by the University of Twente & Cooll SES. It is based on compressor cells and components developed for the DARWIN mission[6].
- An optimized turbopump Holweck-type room temperature compressor developed by Institut Néel/CNRS and Air Liquide Advanced Technologies.

The linear compressor from JAXA-SHI is the most mature solution. The sorption compressor from COOLL has the advantage to generate no micro-vibration and has quite low power consumption (<10 W). The Holweck compressor needs to be space qualified but it is an interesting alternative to the linear compressor in terms of micro-vibration (operate at 1,000 Hz instead of 50 Hz) and a small mass (~2.2 kg instead of 20 kg).

HOLWECK COMPRESSOR

The Holweck compressor is a molecular drag pump. It is often used as the last stage of a commercial turbo-molecular pump. It consists of helicoidal grooves that drag the fluids in the Knudsen regime. The high speed rotor transfers its energy to the particles of the gas along the grooves. Figure 3 shows a cross section of such groove with all the critical dimensions. The depth of the grooves is progressively increased in order to increase the pressure from 5 mbar to 200 mbar.

This pump has been designed and manufactured according to the main requirements from the CCDR (see Table 1). The sizing of the pump has been done thanks to an analytical model developed by Institut Néel/CNRS[7]. The model has been validated from an existing commercial Holweck-type pump from Adixen. This model provides the sizes of the grooves, the diameter of the shaft, the radial clearance between the rotor and the stator, the length and the helix angle.

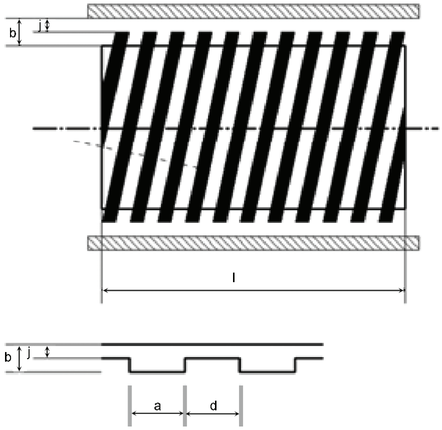

Figure 3. Geometry of the Holweck pump

Table 1. - Requirements for the CCDR ^3He compressor

Temperature	300 K
Inlet pressure	5 mbar
Outlet pressure	200 mbar
Flow rate	30 µmol/s
Working gas	^3He
Electrical power	<100 W

The tests on the manufactured model are presented on Figure 4. It shows the pressure difference versus the inlet pressure for two different speed (700 Hz/42 krpm and 900 Hz/54 krpm) at zero flow. In the viscous regime, the pressure difference should scale with the shaft speed and is apparent above 10 mbar. However at lower inlet pressure, the viscous regime is left due to the rarefaction of the gas and the differential pressure decreases as the inlet pressure decreases. We see that for an inlet pressure of 5 mbar, the outlet pressure is 200 mbar as specified.

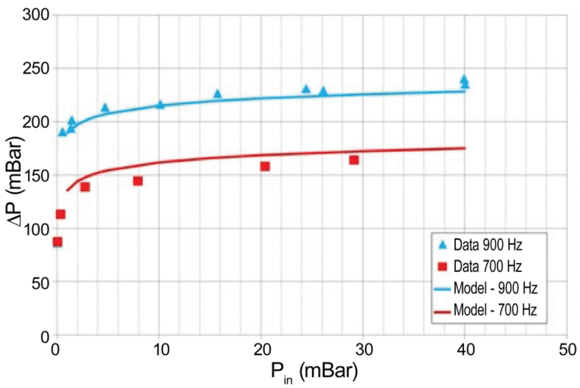

Figure 4. Compression ratio versus the inlet pressure. It has been done for 2 different shaft speeds (42krpm and 54krpm) at zero flow. The points are the experimental points and the lines are the model.

The prototype is mounted on balls bearings and we measure, for a total electrical power of 100 W, less than 50 W losses in the bearings. For space application, balls bearings are not suitable in terms of reliability. They will be replaced by gas bearings (MELFI heritage in Air Liquide Advanced Technologies) or by magnetic bearings already used in other space qualified turbo pump.

From an analytical model validated by an existing pump it can be seen that a prototype of a Holweck-type pump that meets the requirements for the CCDR can be built. From this model, we could adjust the design of the pump to be integrated in other applications like the first stage of a turbo-molecular pump or the first stage of JT cooler in order to reduce the outlet pressure of the JT down to 10 mbar (current JT coolers have a downstream pressure of about 100mbar).

INTEGRATION ON FUTURE SPACE MISSION

In order to reach a cooling power of 1µW at 50 mK, the main requirements for the CCDR are the following:

- A heat sink at 1.7 K with a cooling power available of about 5 mW.
- A ^{3}He pump with a flow rate of 15-30µmol/s and an outlet pressure of at least 100mbar in order to re-condense ^{3}He at 1.7K.

Compare to the OCDR, the CCDR provides important improvements for future space mission with a longer lifetime, a lower temperature with a higher cooling power. It has already been studied at a system level for space mission like SPICA[8], ATHENA/IXO[9] or COrE[10]**.**

Another way of reaching a sub-Kelvin temperature is the use of an Adiabatic Demagnetization Refrigerator (ADR)[11] which is more mature than the CCDR. However, the CCDR has many advantages as compared to the ADR:

- the counter flow heat exchanger provides several thermal anchor from 1K to 50mK for electrical wiring and support structure instead of a few discrete pre-cooling stages.
- the CCDR does not generate any magnetic field that may affect the detectors strongly sensitive to residual magnetic field
- the absence of magnets and magnetic shielding makes the system much lighter (3-10 kg for the ADR, as compared to 1kg). This is of great importance. The focal plane assembly (FPA) on a future mission will have a higher mass than on Planck (currently the FPA is around 6kg).
- CCDR operation is intrinsically continuous which avoids thermal cycling and slow thermal relaxation.

CONCLUSION

The CCDR provides strong advantages compare to current system planned on future space mission and satisfy the current requirements of the missions. The main constraint for the cooling chain is to be able to provide a cooling power of about 5 mW at 1.7 K.

A prototype with all the low temperature elements (mixing chamber, still, fountain pump and counter flow heat exchanger) in a single set up should be tested this year and a coupled test with space compatible ^{3}He compressor is planned this year too. Those tests should bring the CCDR to a Technology Readiness Level (TRL) compatible mission requirement of the Phase B studies.

The Holweck-type pump as a ^{3}He circulator seems to be a good solution since it is a compact solution with a low mass and reasonable power consumption. We also show that this compressor can be applied to a variety of other applications like in 1K class JT cooler or turbo molecular pump.

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