Turbo-Brayton cryocooler suitable for on-board electrical propulsion

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Abstract. Absolut System is building a 40 K vibration-free cooler for ESA earth observation program. This application required small cooling power in the 40 K temperature range but extremely low exported vibration level, high efficiency and mass competitive technology. In addition, a scale-up of the product is on-going to offer a lightweight solution for superconducting motors for hybrid-electric propulsion system. The hybrid-electric propulsion system for transport aircraft required extremely high power to mass ratio and the turbo-Brayton cooler offers a very competitive solution. Finally, the turbo-Brayton technology is also a candidate for electrical space propulsion system. This market combines the constraints of the earth observation system and the HTS application for electrical propulsion on-board transport airplane. Absolut System is then working to combine the two developments toward an integrated solution for electrical propulsion.

1. Introduction

Lightweight and compact systems are key elements for suitability of superconducting systems for aircraft and spacecraft applications. The superconductive wires allow to carry extremely high currents which make feasible the development of disruptive technologies for on-board applications. It is the case for example with hybrid-electric propulsion in aircraft [1] or electric space propulsion [2], cosmic radiation shields, and thermal protection systems for hyperbolic atmospheric entries [3].

The development efforts performed by scientific community during the last 10 years revealed significant improvement on superconductive wires and devices. The robustness of the wires strongly improved and the magnets performances demonstrate they can offer a competitive alternative to conventional electromagnetic systems. However, to become a "game changer" for on-board applications, the superconductive device must be considered as a whole system including the cooling system needed for its operation. The cooling system must be at the same level of maturity than the superconducting part of the system if we want to have a chance to use it.

Today, most of the time, the cryogenic system is considered as an ancillary equipment, used for ground testing [4][5] and the on-board version of cryocoolers are not matured with the same dynamism than superconductive components. However, at the end of the day, the complete system will be evaluated and confronted with conventional technologies.

The work performed by Absolut System and presented in this paper concerns the development of a suitable cryocooler technology able to operate superconducting technologies on-board aircraft and spacecraft.

2. Description of the Turbo-Brayton technology

The main characteristics and criteria required for on-board cryocoolers are the capabilities to provide cooling power with the highest power to mass ratio, a lifetime and a reliability compatible with 10 years operation, a mechanical robustness compatible with launch loads and an integration capability allowing an efficient thermal and power control of the cryocooler.

Absolut System benefits from a large background in cryocoolers development using Joule-Thomson, Stirling, Pulse Tube and Turbo-Brayton technologies. Based on this background and knowledges in the design and manufacturing of each technologies, the different options have been evaluated and confronted with the objectives of on-board cryocoolers. Following this evaluation, a reverse Turbo-Brayton cooler concept has been proposed and developed. The main advantages of this technology are as follow:

- High power density due to high speed compressor and expander,
- Gas bearings providing non-contact operation so high reliability and compatible with >10 years lifetime requirements,
- High efficiency thermodynamic cycle over the 4 K – 300 K temperature range. Cooling power can be upscale easily in this temperature range,
- Possibility to implement precooling using radiators or cryogenic storage,
- Flexible integration capability due to continuous flow. Remote cooling could sort out integration issue in high magnetic field environments,
- Distributed cooling over large surfaces like radiator, cryogenic tanks or thermal shields,
- Multiple loads at single or multiple temperatures,
- Inherently vibration-free below 1 kHz so that no vibration cancellation electronics is required,
- No damping structure and launch locking required.

For all these reasons, the reverse Brayton technology has been selected by Absolut System for on-board applications. The Turbo-Brayton cycle cryocooler uses miniature, high-speed turbomachines and high-effectiveness counter-flow exchangers (or recuperators) to provide high power density, efficient cooling with low vibration and high reliability. Gas bearings are used in the miniature machines to support the rotors, which operate at very high speeds from 300,000 to 600,000 rpm. The low-mass rotors are the only moving parts in the systems, and because they are precision balanced, the systems are inherently vibration-free. No additionnal vibration cancelation through electronics or hardware is required. The gas bearings also provide no-contact operation, so performance degradation resulting from wear or the accumulation of debris is absent. These systems are generally capable of maintenance free operating lives of 5 to 20 years.

Figure 1. Example of different cryocoolers developed and produced by Absolut System (from left to right: LPT6510 2 W @ 80 K Pulse tube with TCBV, 0.5 W @ 130 K High frequency Pulse Tube, 0.5 W @ 150 K Joule-Thomson, 2 W @ 40 K turbo-Brayton, 1500 W @ 77 K High capacity Pulse tube)

Turbo-Brayton cryocoolers may be arranged in a number of configurations to meet a variety of cooling requirements. They are continuous-flow systems made up with appropriate numbers of compressors, expansion turbines, recuperative heat exchangers, and thermal interfaces. These components may be integrated into a compact package or distributed over fairly large areas, interconnected by lengths of tubing. Refrigeration can be delivered to multiple loads at either a single temperature or several different temperatures. The second type of delivery can be accomplished either by multi-staging an integral cooler or by combining several cryocoolers at the appropriate interfaces. Cooling loads and thermal interfaces may be separated by large distances without significant effects on overall system efficiency. Thus, the turbo-Brayton cryocooler can be implemented in a variety of ways in space applications and particularly where large heat flux need to be removed at several locations (like it could be the case for superconducting devices).

The Turbo-Brayton cycle is also known to have a very good efficiency and is suitable for providing refrigeration over a broad range of temperatures. In the frame of the superconducting applications on-board aircraft or spacecraft, the operating temperature range focused in between 40 K and 80 K. In this temperature range, the turbo-Brayton technology benefits from a large background and no specific restriction on the size of internal components is expected (like it could be the case at low power and low temperature operation). The architecture of the reverse turbo-Brayton cycle proposed is presented in the Figure 1 here below.

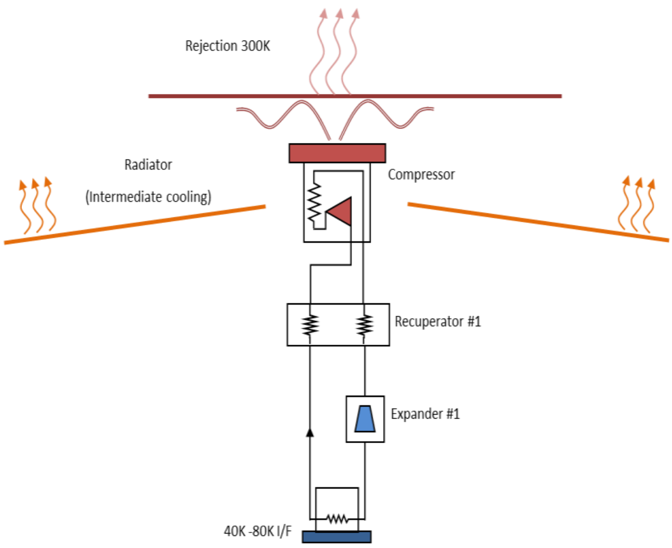

Figure 1. Baseline architecture of the 40-80 K vibration-free Brayton cooler

This schematic constitutes the baseline architecture of the cooler. The centrifugal compressor operates at ambient temperature close to 300 K. A part of the compression power is rejected through a radiator or heat exchanger pending the final application. Then the compressed gas is precooled along a recuperator (counter-flow heat exchanger) before entering the turbine where it is expanded.

The cold gas flows through a user heat exchanger to cool the load (HTS device, thermal shield, focal plan…) and goes back to the counter-flow heat exchanger up to compressor. This concept is the simplest way to build a turbo-Brayton cooler.

For on-board superconducting applications, we based our development on the heritage gained during the development of a vibration-free turbo-Brayton cooler for ESA [6] (Technical Research Program 40001 13495/15/NL/KML). Figure 2 shows the 40-80 K Vibration free cooler after final integration. This cooler is developed for Earth observation application where cooling power in the range of 2 W @ 40 K to 8 W @ 80 K is required to cool infrared detectors. This cooler has been sized to offer an alternative to current Stirling and Pulse Tube flight cryocoolers, while offering vibration-free system. However, its cooling power will be limited to cover future superconductive systems application.

We evaluated, based on different system studies and architecture's analysis, that the cooling power required for most of the on-board applications will be 100 W – 500 W in the 40 K – 80 K temperature range. For this reason, a new cryocooler will be developed using the technologies used for the Earth observation application.

The cooler will use a single compressor operating in the 350.000 rpm to 400.000 rpm rotation speed range. With the background gained on the 40-80 K Vibration free cooler, we know we can operate the compressor at higher rotation speed and suppress one compression stage. The hydrodynamic gas bearings technology will be kept for the compressor and the expander [7]. This technology has demonstrated its flight capability on-board ISS [8] and has been successfully downscaled for small shafts and high rotation speed in the frame of our 40-80 K vibration free cooler.

The recuperator will be fully redesigned for the new cryocooler in order to improve its performances. Its internal configuration and its material will be challenged to reduce the mass while offering the required mechanical robustness.

The targeted mass for the new 500W@80K cryocooler is 30 kg for the complete cryocooler package.

Figure 2. 40-80 K vibration-free Brayton cooler developed for Earth observation application – ESA contract 40001 13495/15/NL/KML

3. Applications of HTS for space propulsion: SUPREME

HET (Hall Effect Thruster) and AF-MPD (Applied-Field MagnetoPlasma Dynamic) thrusters are the main candidates for high power electromagnetic propulsion systems. The HET has the advantage to offer a simple architecture and a high maturity level, especially for low power systems (up to 5 kW). However this technology becomes difficult to upscale because the size and mass increase exponentially with electrical power requirement (see Figure 3).

In the AF-MPD technology, the thrust is generated by the Lorentz force resulting from the interaction between the current flowing through the plasma and the magnetic field (applied externally in our case). This technology allows to achieve very high exhaust velocities (up to 100 km/s), high specific impulse (3,500 s using Argon and potentially up to 5500 s with CH4 or 8000 s with H2)) and high thrust (up to several Newton, which is quite high for electrical propulsion). The main drawback of this technology is the high DC current required by the copper coils to generate the magnetic field. The thermal management of this coils is extremely critical and limits the development of this technology.

However, today, the high temperature superconductors allow to solve this major issue of AF-MDP replacing the conventional copper coil with HTS coil. HTS are clearly “game changers”, as explained in [9], for this technology due to a significant reduction of electric power and mass of coils, combined with a significant increasing of the magnetic fields (see comparison with HET in Figure 3). The use of HTS neutralizes the issues linked to the Applied-Field systems providing current density up to 100 times larger without compromise on the performances. This connection between technologies opens a large field of applications: Space-tugs for orbit-raising of large satellites; Cargo and transport logistics for lunar/martian missions; High Delta-V interplanetary transfers to Mars and near-Earth objects.

In that frame, the SUPREME consortium, in conjunction with EU Horizon 2020, is developing a laboratory breadboard prototype of superconducting AF-MPDT incorporating HTS coils, with a view to reaching Technology Readiness Level (TRL) 5 by the end of 2022.

This will be achieved by producing firstly an engineering qualification model of the thruster, corresponding to TRL 6, by the end of 2024. This will be followed by a qualification campaign and thereafter the production of a flight-qualified model and demonstration taking place in 2028.

Absolut System is in charge of the development of the equipped cryostat including the superconducting coil (provided by Theva) and the complete cooling system. A powerful, compact and lightweight cooling system is required for this project to enable the AF-MDP to achieve its performance objectives. The turbo-Brayton cryocooler under development for on-board applications will be adapted to match the final cooling power requirement. The turbo-Brayton cooling power can be adapted easily without major redesign to fit with various AF-MDP power.

The continuous gas flow in the cooler will be used to absorb the dissipation of the current leads and the HTS coil support. The thermal shield required between the cryostat and the thruster will be actively cooled as well at higher temperature.

Furthermore, the cryocooler could be used for propellant storage. The cryocooler could be used to extend the storage capacity of the tanks by increasing its density (liquid or supercritical propellant).

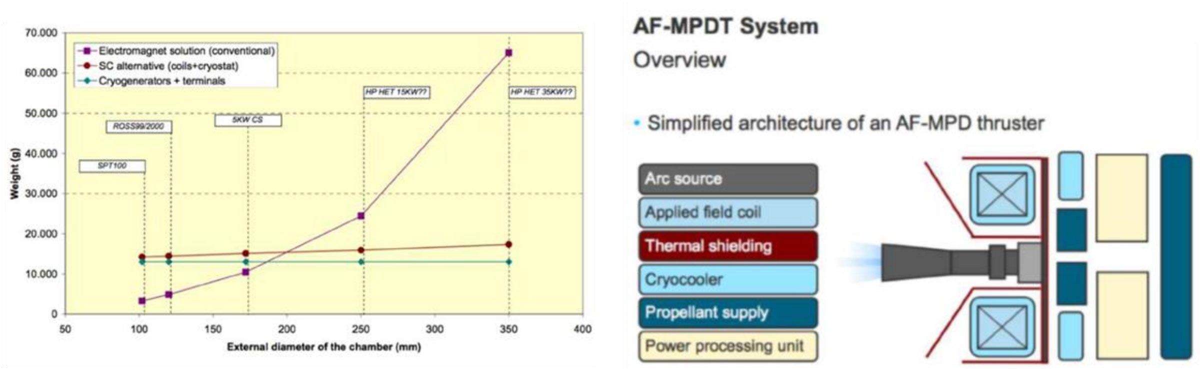

Figure 3. Weight increase of magnetic generator on up-scaling: conventional electromagnets vs superconducting solution (LEFT), Schematic of Superconducting AF-MPD thruster (RIGHT). Courtesy of SUPREME consortium

4. Applications of HTS for hybrid-electric propulsion

In parallel to the cryocooler development, Absolut System through its sister company AFCryo, designed and manufactured a 50 kW superconductive motor (see Figure 4). The specification of the prototype was to achieve 50 kW of mechanical power while running at 5000 rpm.

The objective of this project was to realize a superconducting machine using high temperature superconductors known as HTS. The motor uses a hybrid configuration with a superconducting rotor while the stator is made of copper, as for conventional electric machines. The outcomes of this project is to design, produce and test this prototype of superconductive motor and extrapolate its capabilities at larger power (such as a Megawatt range).

The test of the motor is performed using a laboratory helium cooling loop produced by Absolut System [10]. This test set-up is very flexible for such a test but can't be used for the final application. The next step of the HTS motor development will be to couple the turbo-Brayton cooler with this HTS motor to evaluate the complete chain.

Figure 4. 50 kW HTS motor. HTS coil on the right, front and rear view in the middle, rotor with HTS magnet on the right

5. Conclusions

Absolut System developed the key technologies required for the development of superconducting devices on-board aircrafts or spacecrafts.

The coupling during the development phase of both electromagnetic components and thermal management system is a key factor to achieve the success of the final product development.

For this reason, Absolut System increased its involvement in both aspects, with the cryocooler development on one side and the design and manufacturing of superconducting systems on the other side in collaboration with its sister company AFCryo, laboratories and HTS coils manufacturers.

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