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Article

A Turbo-Brayton Cryocooler for Future European Observation Satellite Generation

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ABSTRACT

Several types of active cryocoolers have been developed for space and military applications in the last ten years. Performances and reliability continuously increase to follow the requirements evolution of new generations of satellite: less power consumption, more cooling capacity, increased life duration.

However, in addition to this increase of performances and reliability, the microvibrations requirement becomes critical. In fact, with the development of vibration-free technologies, classical Earth Observation cryocoolers (Stirling, Pulse Tube) will become the main source of microvibrations on-board the satellite.

A new generation cryocooler is being developed at Absolut System using very high speed turbomachines in order to avoid any generated perturbations below 1000 Hz. This development is performed in the frame of ESA Technical Research Program - 4000113495/15/NL/KML.

This paper presents the status of this development project based on Reverse Brayton cycle with very high speed turbomachines.

INTRODUCTION

The space cryogenics sector is characterized by a large number of applications (detection, imaging, sample conservation, propulsion, telecommunications etc.) that lead to various requirements (temperature range, microvibration, lifetime, power consumption etc.) that can be met by different solutions (Stirling or JT coolers, mechanical or sorption compressors etc.).

The recent years saw, in Europe, the developments of coolers to meet Earth Observation mission requirements that are capable to provide significant cooling power at an operational temperature around 50K (for IR detection). Those single stage Stirling or Pulse Tube coolers are mechanisms that involve moving parts at low frequency (in the compressor and in the Cold Finger for the Stirling) which induce microvibrations. Even if active microvibration cancellation and careful screening and manufacturing of the coolers parts can lead to low exported microvibrations (< 100 mN in all directions at all harmonics), more and more stringent system level induced microvibration requirements can lead to very complex solutions to overcome those vibrations (e.g. suspended coolers and radiators, flexible thermal link assemblies that degrade the overall thermal performances).

With the development of vibration-free technologies (magnetic bearing reaction wheels, microthrusters), classical Earth Observation cryocoolers (Stirling, Pulse Tube) will become the main source of microvibrations on satellites. To overcome this difficulty and cope with missions that have more and more stringent pointing performances requirements, it is necessary to develop alternative cooling solutions or to adapt current technologies to generate no mechanical disturbances.

The objectives of the activity presented in this paper are to design, manufacture and test an Elegant Breadboard Model (close to an Engineering Model) of a “Vibration-Free” cooler that can provide active cooling for temperatures in the range of 40-80 K in order to answer the needs of potential future Earth Observation IR missions.

DEFINITION OF THE PROPOSED SOLUTION

In order to meet the performances requirement and particularly the vibration-free constraint, a reverse Turbo-Brayton cooler concept has been proposed. The Turbo-Brayton cycle cryocooler uses miniature high-speed turbomachines and high-effectiveness recuperators, to provide efficient cooling with low vibration and high reliability. Gas bearings are used in the miniature machines to support the rotors, which operate at speeds of 100,000 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 supplemental vibration canceling electronics or hardware is required. The gas bearings also provide non-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.

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 of 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 multistaging 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.

The Turbo-Bratyon cycle is also known to have a very good efficiency and is suitable for providing refrigeration over a broad range of temperatures. It is generally more efficient at higher loads and temperatures but operation as low as 4.2 K has been demonstrated. Decreases in performance in coolers of low capacity (less than 1 W) are primarily a function of the manufacturing technologies used in producing the small turbomachines and the recuperators. System mass and thermodynamic performances are both strongly influenced by specific design features in these components.

The in-orbit operation of these technologies during more than 10 years represents a successful demonstration of their maturity [1][2]. Today, new developments are running in the US through Creare LLC. to cover a large range of operating temperature and cold power. These new developments are also oriented to increase again the turbo-Brayton cooler efficiency by increasing the rotational speed of turbomachines up to 10,000 rev/s (600,000 rpm) [3].

The Turbo-Brayton is thus the most relevant technology to fulfill:

- a nominal operation along the required temperature range (40 K and 80 K)
- a vibration free requirement because of the the rotational speed larger than 2000 Hz which is far above the critical bandwith required for the system [0 – 1000 Hz]

The architecture of the reverse turbo-Brayton cycle proposed is presented in Figure 1.

This schematic constitutes the baseline architecture of the cooler. The centrifugal compressor is heat sunk on a 300 K radiator (the radiator surface required is below $1m^2$). Then, the counter-flow heat exchanger is used to precool the gas before entering the turbine where it is expanded. The cold gas goes through a heat exchanger to be connected to the load to be cooled and goes back to the counter-flow heat exchanger up to compressor. This concept is the simplest way to build a turbo-Brayton cooler.

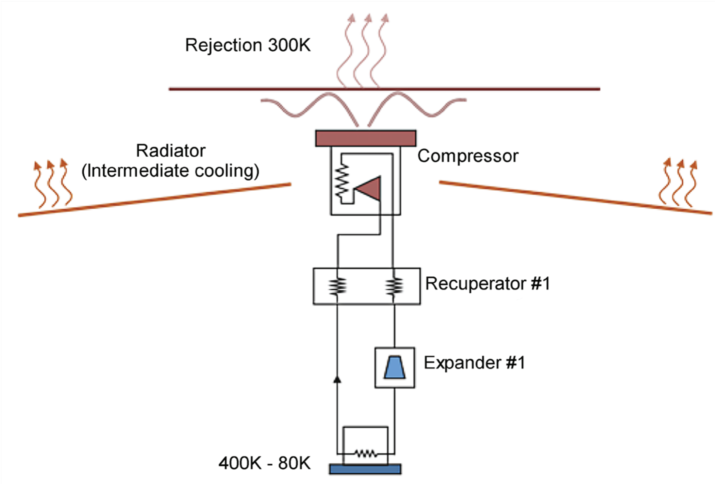

Figure 1. Baseline architecture of the 40-80K vibration-free Brayton cooler

SYSTEM TRADE-OFFS AND ANALYSIS

In order to optimize our cryocooler concept, several points have been analyzed during the first phase of the development. The different aspects confronted during the trade-off phase were focusing on the technologies to be used and the overall architecture of the system. As part of these different trade-offs, the following points have been discussed and assessed.

Number of compressor stages

The efficiency of the compressor is clearly a driver in this trade-off due to the strong impact of this parameter on the cryocooler input power. The other aspects analyzed in this trade-off are: the mass, the reliability, the modularity of the system, the manufacturing and integration issues, and the on-ground tests complexity.

Regarding the efficiency, the same isentropic efficiency can be reached by the single stage or two-stage compressor. The main difference is that the rotational speed drastically increases for the one stage compressor. An efficiency larger than 0.5 is reached at 240K rpm using two impellers. With only one impeller, rotational rate of 380K rpm is needed to reach the same efficiency of 0.5.

It has been estimated that a 2-stage compressor will operate at lower rotational speed and thus will lower the technical risks for this first development without significant impact on the compressor performance.

Compression stage arrangement

We have seen that the baseline compressor design is a 2-stage compressor. However, several options exist to arrange these 2 stages :

- The in-line arrangement is more compact but results in lower compressor efficiency due to the relatively sharp inter-stage flow distribution. As a result of these flow losses, the aerodynamic stage efficiency of an in-line two-stage compressor is lower than the single stage machine.
- In a back-to-back compressor design, each stage can be designed as a single stage machine with corresponding high stage efficiency. One of the advantages of the back-to-back configuration is obviously in term of rotor dynamics and axial load. The compressor is more balanced in this configuration. However, the flow distribution will impact the performances even if the figures should be lower than in the in-line arrangement.
- Finally the separated architecture is an arrangement with two separated compressors.

This last option (separated architecture) has been identified to be most desirable due to:

- Its modularity forease of integration.
- An optimum circulation of fluids (so optimal aerodynamic efficiency).
- Two identical designs. In our case, the impellers and the motors are strictly identical and interchangeable.
- Possibility to arrange easily inter-stage cooling (efficiency improvement).

This last arrangement concept strongly decreases the complexity of the rotor integration and will allow a more efficient management of the high precision parts.

Choice of the working fluid

Based on the operating temperature of the cooler, the working fluid needs to be optimized. In the expected operating temperature range, neon and helium can be used as a pure fluid or a mixture. Several configurations have been analyzed with pure neon as the baseline. An optimum has been found by analysis on the proportion of helium added in the pure neon. With 20 % of Helium, the cooling power increases by about 20% at 40 K but needs an increase of the compressor rotational rate up to 300K rpm (instead of 250K rpm). In order to limit the technical risks and to be conservative on the cooling power, pure neon is used for detailed design.

Recuperator technology

Different technologies have been used for the recuperator. The recuperator is one of the most critical component regarding the overall cycle efficiency. Thus, the choice of the technology to be used for our application needs to be carefully addressed. The objective of this trade-off is to confront different technologies identified as good candidates for our needs and then to evaluate their potential for the final cryocooler.

The different technologies identified are:

- The micro channels heat exchangers
- The parallel plate heat exchangers
- The metallic foam heat exchangers
- The microtube heat exchangers

For each technology, a preliminary design has been proposed and the associated performances determined. These inputs have been considered for the trade-off and the selection of the nominal technology. The baseline concept uses a microtube recuperator concept as proposed by Mezzo Technologies [4], which offers the best ratio of efficiency to mass.

SYSTEM DESCRIPTION

Following the trade-off activity run in parallel of the component design and optimization, the preliminary design of the 40-80K reverse Brayton cooler has been consolidated.

The 40-80 K vibration free cooler is composed of the following sub-systems as seen in Figure 2:

- A 2-stage centrifugal compressor.
- A microtube recuperator.
- A cryogenic expander (including a cold electrical generator).
- An external supporting structure.

2-stages centrifugal compressor

The compressor consists in a pair of identical units shown above in series formation. Each units contains a centrifugal compressor wheel optimized to be operated at 250,000 rpm, supported on gas bearings and driven by a permanent magnet motor. The neon gas flows through each compressor stage; the first is a low pressure stage and the second a high pressure stage.

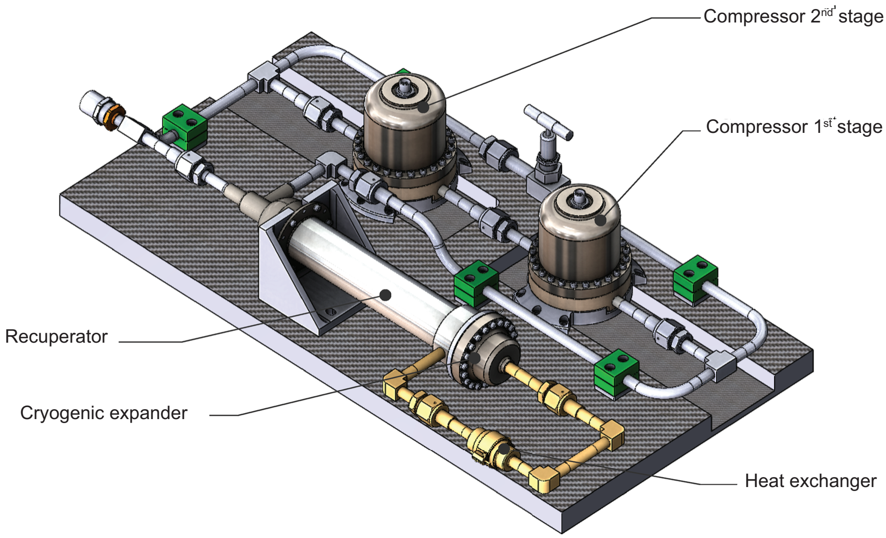

Figure 2. Overview of the 40-80 K vibration free cooler

Figure 3 details the internal structure of the centrifugal compressor. The compressor is composed of a Ti6-Al4-V cartridge where the rotor and stator components are mounted. The cartridge is then mounted in the external housing and sealed with metallic seal. Due to the relatively small change in density between stages, it was realized that one design of compressor could be applicable for both stages with minimal decrease in efficiency. This would simplify the design and manufacture process and require a smaller parts inventory. To allow this, approximately equal enthalpy rises are required on each stage, as the impeller will produce a fixed loading. Pressure ratios are then split between the two stages at about 1.40 and 1.32.

Rapid evaluation of design changes were made by using the internal 1D tools and final design was consolidated using CFX (CFD code). The design features backswept blades to achieve a high relative velocity ratio (and hence good surge margin), a vaneless space diffuser in order to also maximize the flow range, followed by a volute and conical exit diffuser, to maximize the static pressure recovery.

The full stage CFD model is shown in Figure 4, and full stage CFD predictions were carried out for both stages over a range of flows, and combined to produce an overall characteristic at 250,000 rpm. A peak overall total-static efficiency of about 57 % is predicted, while the overall pressure ratio target of 1.85 is exceeded slightly with both stages running at 250000 rpm. It is expected

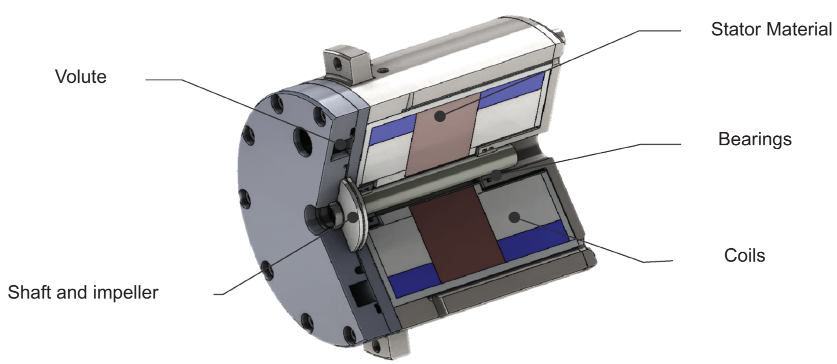

Figure 3. View of the compressor cartridge

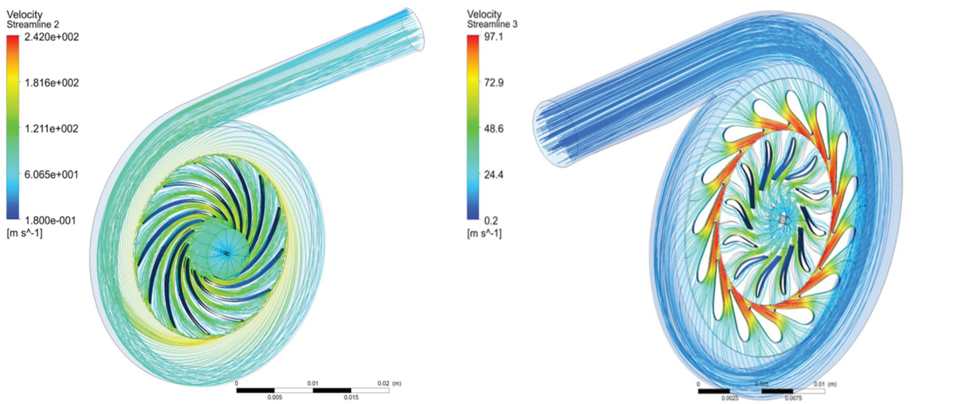

Figure 4. CFD Model (using CFX) showing streamlines (compressor on the left, expander on the right)

that further optimization at the detailed design stage may improve the efficiency slightly, and that the target of 59 % should be achieved.

The gas bearings to be used here are of the spiral groove type. These are identical in form to those used both in the MELFI project and Atlas Copco Helium expander [5], all designed using the same methods by the same experts. The journal bearings are herringbone grooved with a plain portion between symmetric patterns. These gas bearings guarantee stability and load capacity and require no adjustment or setting up once manufactured. The Figure 5 shows a typical spiral groove journal bearing.

The motor design achieves low values of electromagnetic loss in all forms (core loss, ohmic winding loss, flux harmonic and other stray sources), combined with low windage loss, which in combination are unusually low for the power rating and speed, due to careful attention to the proportions of component parts and choice of materials. The main features of the motor are:

- A cylindrical two-pole rare-earth magnet contained within a tubular shaft of material that is mechanically stiff and strong, non-magnetic, and with at least moderately high resistivity. The surface of the shaft also provides the rotating part of the gas bearings at each end of the machine.
- A multi-tooth stator core containing a 3-phase winding

Following the estimation of the different losses of the compressor, the overall efficiency has been analyzed and a global powertrain efficiency of 47% is estimated considering the different contributions regarding the electrical losses, windage losses, bearings and impeller losses.

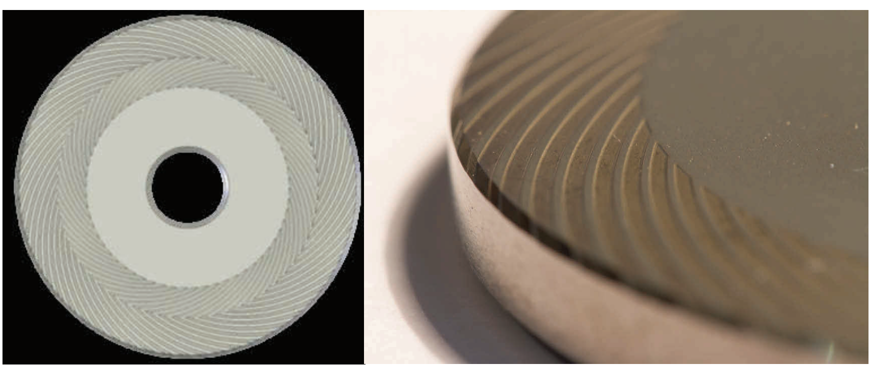

Figure 5. Typical spiral groove journal and thrust bearing

Microtube recuperator

The recuperator is based on microtube heat exchanger technology. One advantage of this technology is that the recuperator is quite compact compared to other technologies. The recuperator has a cylindrical shape with the junctions on the two extremities. On the warm end, the recuperator is equipped with a flange which is the mechanical interface between the recuperator and the supporting structure. On the cold end, the expander is directly attached to the recuperator.

This configuration avoids any additional mechanical supports for the expander and thus lowers the thermal losses. The recuperator is shown in Figure 6. It is composed of an external shell made with stainless steel tube with two caps at the extremities where the piping is welded. Inside the shell, microtubes are welded to the end-plates.

The main characteristics of the recuperator are:

- External shell diameter: 41 mm
- Overall length (without piping): 365 mm
- Number of microtube: 2200
- Total mass: 0.81 kg
- Thermal effectiveness: 98.5 %
- Pressure loss (High pressure side): 1000 Pa
- Pressure loss (Low pressure side): 1500 Pa

Cryogenic expander

The cryogenic expander is dedicated to extract power from the fluid flow in order to decrease its temperature. This extraction is made by the gas expansion through a turbine wheel with power absorbed by a permanent magnet generator.

This cryogenic expander is composed of the following key mechanical parts:

- A rotor equipped with a wheel, a shaft and a magnet: the fluid expansion produces a mechanical work with an amount of power transmitted to the rotational shaft.
- A generator (acting like an electromagnetic brake): the shaft power produces then some electrical power in the electrical generator. This electrical power corresponds to the power extracted from the gas. It is then dissipated at the warm end of the cryocooler.
- A stator housing including the gas bearings and supporting plates, the expander housing and its electrical feedthrough, the volute with piping junction

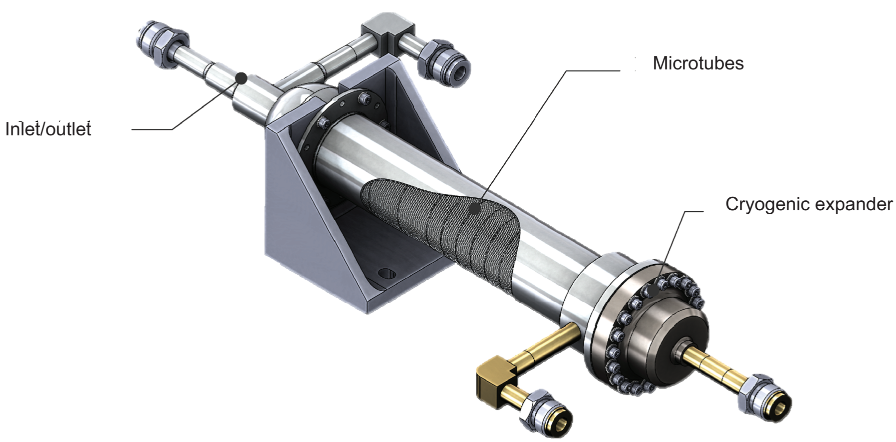

Figure 6. Recuperator design with integrated cryogenic expander

In order to reduce risks, it is intended to use similar techniques and solutions for both compressor and expander sub-systems. The conclusions of trade-offs concerning the compressor design are then directly implemented into the expander design.

The expander consists of a single turbine stage driving the electrical generator. The nominal running speed is 150,000 rpm but this is variable in order to allow control of the starting procedure and for fine tuning of the operating point. The internal architecture of the expander is detailed in the Figure 7.

As with the compressor, a full stage CFD model of the turbine has been constructed and run. The design was iterated in 1-D models and then to CFX to achieve the target flow at the design pressure ratio. The CFD results were adjusted for disc windage and leakage, and resulted in a stage total to static efficiency of 71.4 % - slightly above the target of 71%.

As per the motor of the compressor, the design details of the generator have been developed using Synthet-PM, a design program for high-speed surface-magnet machines developed over many years by OFTTECH and proven by extensive use for commercial machines over a wide range of power and speed. The optimum design is then validated through 3D time-varying finite-element study using ANSYS RMxpert [6] plus ANSYS Maxwell 3D [7], which computes power losses in all parts of the machine together with voltage-current terminal characteristics.

Following the estimation of the different losses of the turbine, the overall expansion efficiency has been analyzed and estimated in the range of 64% (electrical losses, windage losses, bearings and impeller aerodynamic losses).

BREADBOARDING ACTIVITIES

In order to mitigate the different technical risks highlighted during the preliminary design phase, different breadboard activities have been run. These activities concern different aspects of the cooler from system level analysis down to elementary component testing or manufacturing technics validation.

System level analysis validation

The objective of this activity is to perform a critical review of the system level analysis. Several assumptions in the process analysis can have a major influence on the cryocooler design. The objective herein is to perform an independent critical review of the thermodynamic cycle characteristics and trade-off on various performance features selected by Absolut System.

To do that, Creare LLC collaborates with Absolut System as reverse turbo-Brayton expert and their support has been used during the first part of the development phase in that way. During the detailed design phase, Creare LLC is involved in the review of critical design of cryocooler's components and associated manufacturing issues.

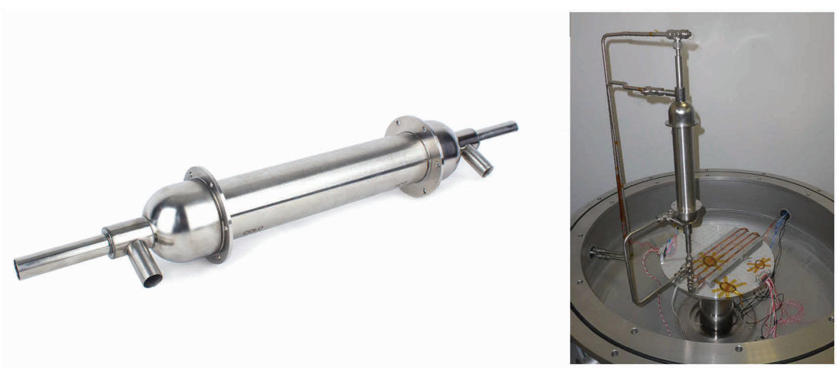

Figure 7. Picture of the recuperator prototype and test set-up in vacuum test chamber

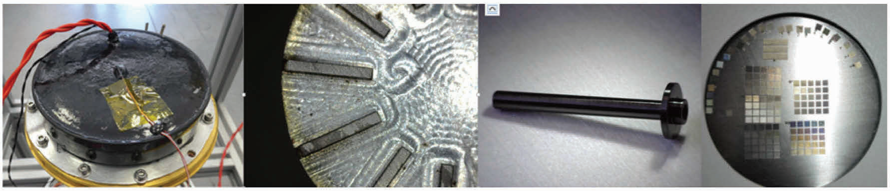

Figure 8. Breadboard samples: stator sample, dummy impeller, dummy shaft for hard coating, grooves manufacturing optimization

Recuperator performance evaluation

As detailed in the system trade-off study, several technologies could be used for the recuperator. A baseline has been selected using microtube heat exchangers and has been evaluated as promising. This technology has been prototyped in order to evaluate the real performances and to validate predicted performances (CFD models)

A prototype has been designed and manufactured to test this technology. The Figure 8 shows the prototype of recuperator manufactured by Mezzo Technologies and its implementation in Absolut System test facilities for characterization.

Stator material characterization

The efficiency of the expander is extremely critical for the cooler performances. However, it is extremely difficult to find in technical literature the electrical properties of conventional materials at cryogenic temperature range.

The evaluation of the internal losses of the generator is then linked to a good empirical understanding of the different losses and particularly permeability and loss density for stator materials. In parallel of the design of the component, a characterization test campaign has been run by Ofttech and Absolut System to measure these characteristics on different materials at different cryogenic temperatures. This yielded to several interesting datum on permeability and loss density for materials of choice, at room temperature and down to 40K (for turbine generator use).

Manufacturing breadboard tests

In complement of the design validation using breadboard tests, some manufacturing aspects like the bearing spiral grooves, the hard coatings on the rotor or the diffusion bonding of the impeller have been validated through dedicated breadboard tests.

CONCLUSIONS AND OUTLOOK

A challenging development programs is on-going in the frame of an ESA contract to provide an alternative to regenerative cryocoolers for future European Earth observation missions. A Turbo-Brayton cooler design has been developed using highly skilled engineers involved in this project with the support of US colleagues.

The detailed design of the 40-80K vibration-free cooler is bound to be finalized after an intensive breadboard test campaign used to lower technical risks and to mature as far as possible the manufacturing design of this cryocooler.

Thanks to this design, our vibration free cooler should be able to produce 1 W @ 40 K to more than 5 W @ 80 K with less than 180 W of electrical power input, satisfying ESA requirements.

ACKNOWLEDGEMENTS

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