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Authors of paper	T. Trollier and A. Ravex (1) I. Charles and L. Duband (2) J. Mullié, P. Bruins and T. Benschop (3) M. Linder (4) (1) Air Liquide Advanced Technology Division, AL/DTA Sassenage, France (2) Atomic Energy Committee, Low Temperature Div., CEA/SBT, Grenoble, France (3) THALES Cryogenics B.V. Eindhoven, The Netherlands (4) European Space Agency, ESA/ESTEC, Noordwijk, The Netherlands

ABSTRACT

A Miniature Pulse Tube Cooler is presently under development in partnership between AL/DTA, CEA/SBT and THALES Cryogenics. The Engineering Model foreseen is aiming to provide 800 mW at 80 K with 50°C ambient temperature and 40 watts maximal input power to the motors of the compressor.

A development phase has been performed with an in-line architecture for the Pulse Tube cold finger connected to an existing flexure bearing compressor from Thales Cryogenics. Presently, more than 900 mW at 80 K has been achieved at 288 K ambient temperature provided by water cooling, in inertance mode and with less than 25 watts PV work.

The development phase is presented as well as the various trade-offs made, both on the cold finger and compressor side, to cope with the thermal, mechanical and electrical environmental specifications. The impact of the matching between compressor and Pulse Tube cold finger is also discussed.

This work is performed in the framework of a Technological Research Program funded by the European Space Agency. An Engineering Model will be delivered to ESA/ESTEC in February 2003. This coming generation of Miniature Pulse Tube Cooler will be used for the cooling down of detectors in future earth observation missions.

INTRODUCTION

The overall objective of the work is to optimise, design, and manufacture at pre-qualification level a 50-80 K Miniature Pulse Tube Cooler (MPTC). The resultant MPTC shall be commercially competitive in performance, mass and cost within the future space cryocooler market. It shall offer significant advantages over the presently available technology and shall require no or only minor delta qualification for direct use in future spacecraft applications. The technical specifications from ESA/ESTEC are summarized in the following table 1.

Cooling power @ 80 K / rejection temperature	800 mW / 323 K
	1240 mW / 288 K
Electrical input power to the compressor	40 Wac
Transfer tube	20 to 50 cm
Mechanical cooler mass	< 2,5 kg
Lifetime	5 years min. 10 years goal
Mechanical loads (sinus, 3 axis)	[5-20.5 Hz] +/- 12 mm peak
	[20.5-60 Hz] +/- 20 g peak
	[60-100 Hz] +/- 8 g peak 2 octave/min
Mechanical loads (random, 3 axis)	20 Hz / 0,016 g^2/Hz
	[20-80 Hz] / +6 dB/oct
	[80-500 Hz] / 0,26 g^2/Hz
	[500-2000 Hz] / -3 dB/oct
	2000 Hz / 0,065 g^2/Hz
	Composite 17 grms

Table 1. MPTC technical specifications summary.

DEVELOPMENT PHASE

A 15 months duration development phase has been performed. During this phase, 9 Pulse Tube cold fingers Development Models (DM) have been designed, manufactured and tested so far. In order to modify easily the geometry for optimisation of the DMs, an in-line configuration has been used for the cold finger. Common materials such as stainless steel and pure copper have been implemented for the tubes and for the heat exchangers as shown in the figure 1. Water cooling is provided at both the hot ends of the regenerator and the tube.

All the DMs have been operated in an inertance mode. Although the introduction of a secondary orifice usually leads to increased efficiencies compared to the simple Orifice Pulse Tube Refrigerator, it also induces some parasitic flow problems. Performance of the Double Inlet Pulse Tube Refrigerator is not always reproducible within a cooler batch. Researchers[1,2] attribute this erratic behaviour to DC flow that takes place in the loop formed by the regenerator, pulse tube and secondary orifice. Asymmetric flow impedance in the secondary orifice can also cause such a DC flow which carries a large enthalpy flow from the warm end to the cold end even for a DC flow of a few percent of the AC flow amplitude. As reported in previous work[3], operation in orifice mode could also lead to efficient pulse tube cryocooler when used with inertance tube. This mode would by definition eliminate the DC flow. Due to this experience, the inertance phase shift control is our preferred operation mode.

The pressure oscillator connected to the pulse tube cold finger Development Models is derived from the new family of tactical Stirling coolers[4] manufactured by Thales Cryogenics B.V. It consists of a unique new generation of long-life, flexure-bearing, linear driven dual opposed pistons oscillator. The linear motor configuration uses moving magnets attached to the pistons that reciprocate inside static coils. The compressors used are capable to provide 4.2 cubic centimeters swept volume for 100 Watts maximal input power to the motors. The outer envelope of the compressor is 60 mm diameter and 165 mm length.

Both compressor and cooler drive electronics are mounted onto a water cooled cold plate as presented in the figure 2.

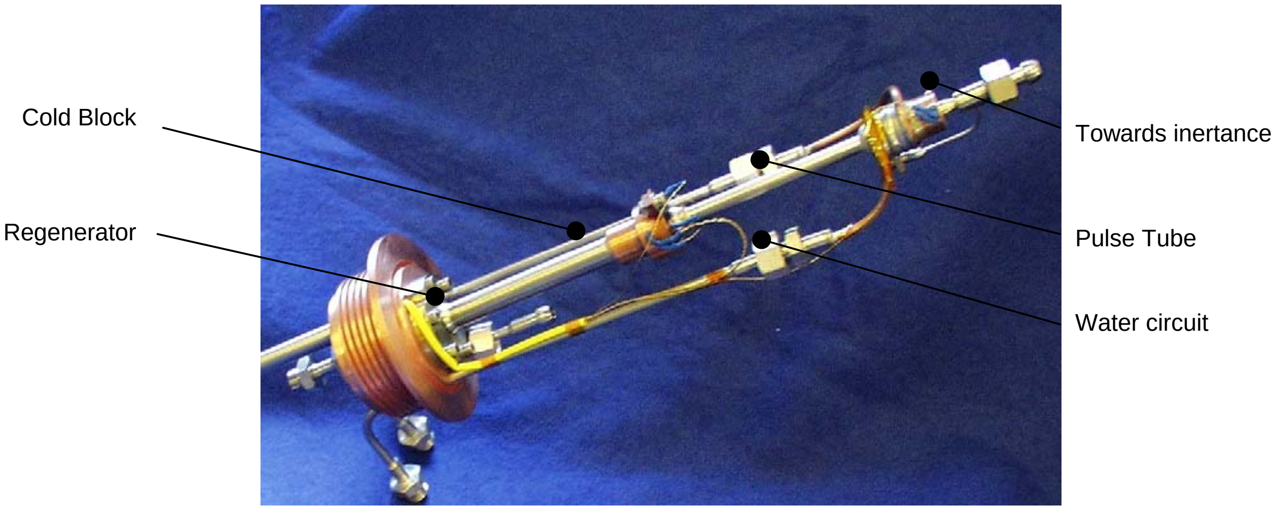

Figure 1. Example of in-line Pulse Tube cold finger Development Model.

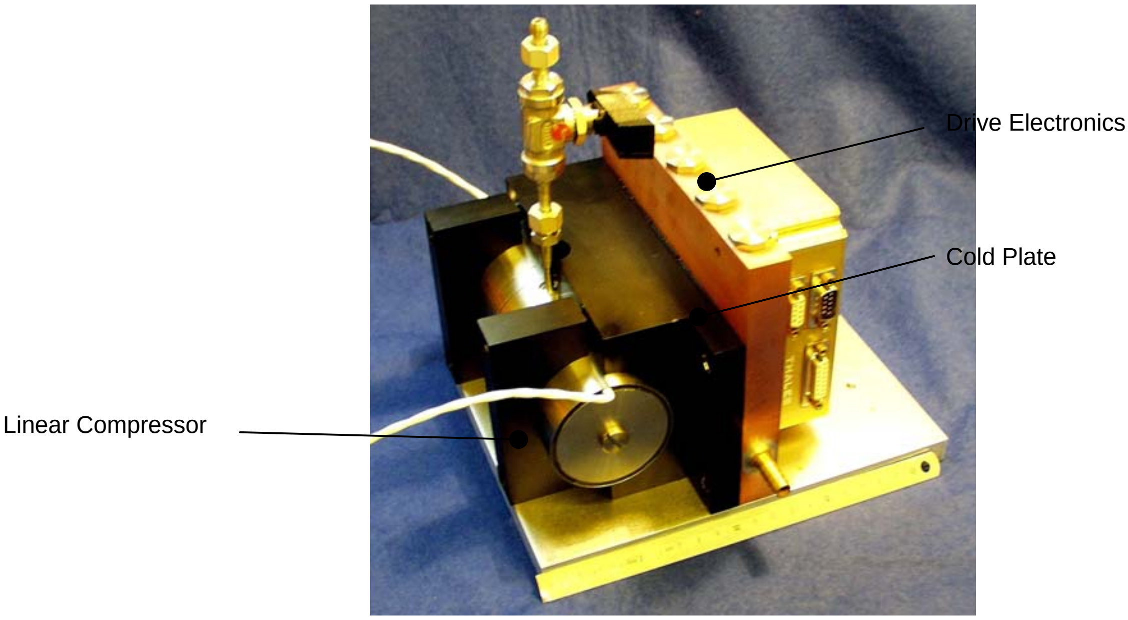

Figure 2. Flexure bearing linear compressor and drive electronics tooling.

PERFORMANCE OF THE DEVELOPMENT MODELS

Each DM has been tuned with various inertance length and diameter for 30 and 40 bars filling pressure and for 40 to 60 Hz operating frequency. The pulse tube cold fingers are operated in vertical orientation, with the warm end of the tube in the upright position. MLI has been wrapped around the regenerator and the pulse tube.

A mapping of the optimal performances achieved with the nine DMs experimented is plotted in the figure 3. Each DM differs from the other with slight changes in the dimensions (regenerator and/or tube, diameter and length), leading to various optimal settings of the inertance and the operating frequency.

The mapping is performed with 288 K heat rejection temperature, 25 watts input corresponding to the electrical input power minus the Joule losses (thus assumed to be close to the PV work) and 20 cm transfer tube between compressor and cold finger.

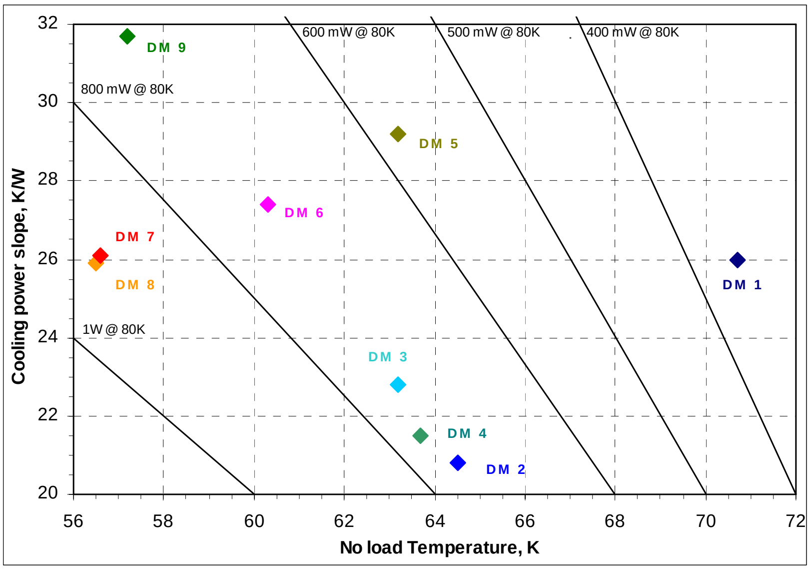

Figure 3. Mapping of the in-line DM performances. 40 bars. 288 K rejection temperature. 25 watts (W-RI^2) assumed as the PV work.

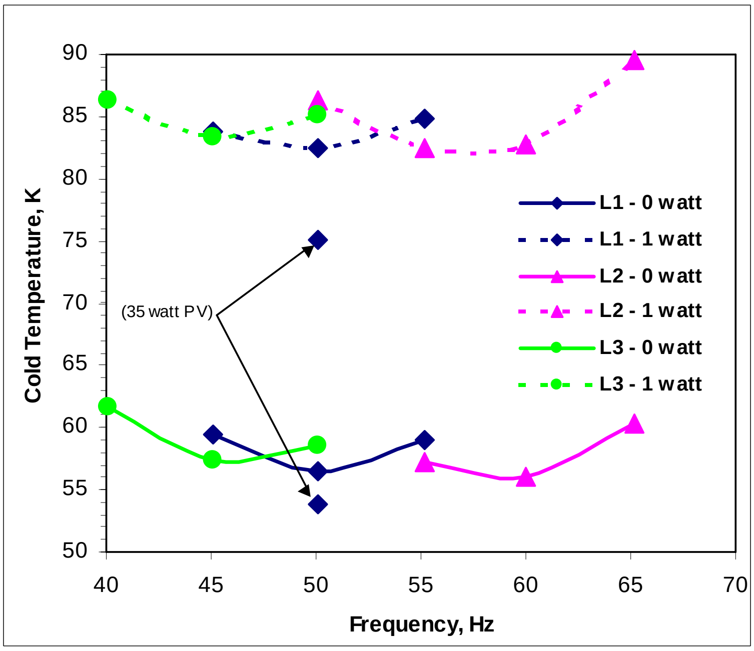

Figure 4. Various settings of the DM #8 with 3 different lengths (L1, L2, L3) of a given inertance diameter. 40 bars filling pressure. 288 K rejection temperature. 25 watts (W-RI^2). Continuous lines indicate the no-load temperature, dashed lines represent the temperature with 1 watt applied heat load.

In the best configuration (DM #8), with 25 W input (W-RI^2), the no-load temperature is 56,3 K and the temperature increases to 82,3 K with 1 watt heat load applied at the cold tip. This performance corresponds to 907 mW of cooling capacity at 80 K, with a cooling power slope of 26,2 K/W. The stroke of the pistons has been measured in such conditions with an LVDT tansducer, leading to a swept volume of 1,50 cubic centimeters.

With 35 W input, the no-load temperature is 53,8 K and the temperature increases to 75,3 K with 1 watt heat load applied at the cold tip. This performance corresponds to 1230 mW of cooling capacity at 80 K, with a cooling power slope of 21,3 K/W. In this case, the swept volume increases to 1,76 cc. Both performances were achieved with 40 bars Helium filling pressure and 50 Hz operating frequency.

The load curves achieved for 25 W and 35 W input (PV work) are reported in the figure 5 below.

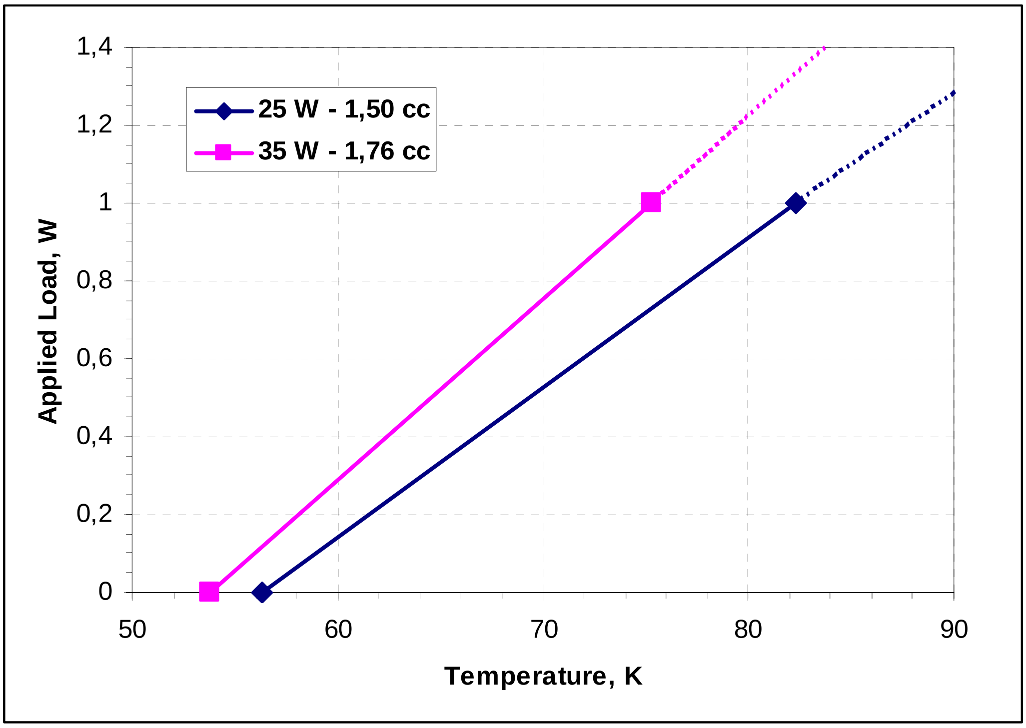

Figure 5. DM #8 load curves. 50 Hz, 40 bars, 288 K rejection temperature.

ENGINEERING MODEL PRELIMINARY DESIGN

Pulse Tube Cold Finger EM

The regenerator and the tube are mounted onto a flange in a U-shape configuration. This configuration has been selected to provide good cryogenic performance in a compact, robust and simple design that enhances the integration compared to an in-line configuration. The flange is made of a specific aluminium material for thermal heat transfer and mechanical resistance optimisation. The hot flange is designed such as it integrates the buffer volume and the heat exchangers of the regenerator and the tubes. The heat exchangers are manufactured by Electron Discharge Machining directly in the flange material. The inertance is wounded inside the buffer volume.

Both the tube of the regenerator and the pulse tube itself are made of thin walled titanium alloy TA6V4 in order to reduce the parasitic heat leaks. The design makes use of bolted flanges and metallic C-rings to seal the regenerator and the tube to the aluminium hot flange. At the cold side, a high vacuum brazing process is used for the assembly of the titanium tubes onto the pure copper cold block of the cold finger.

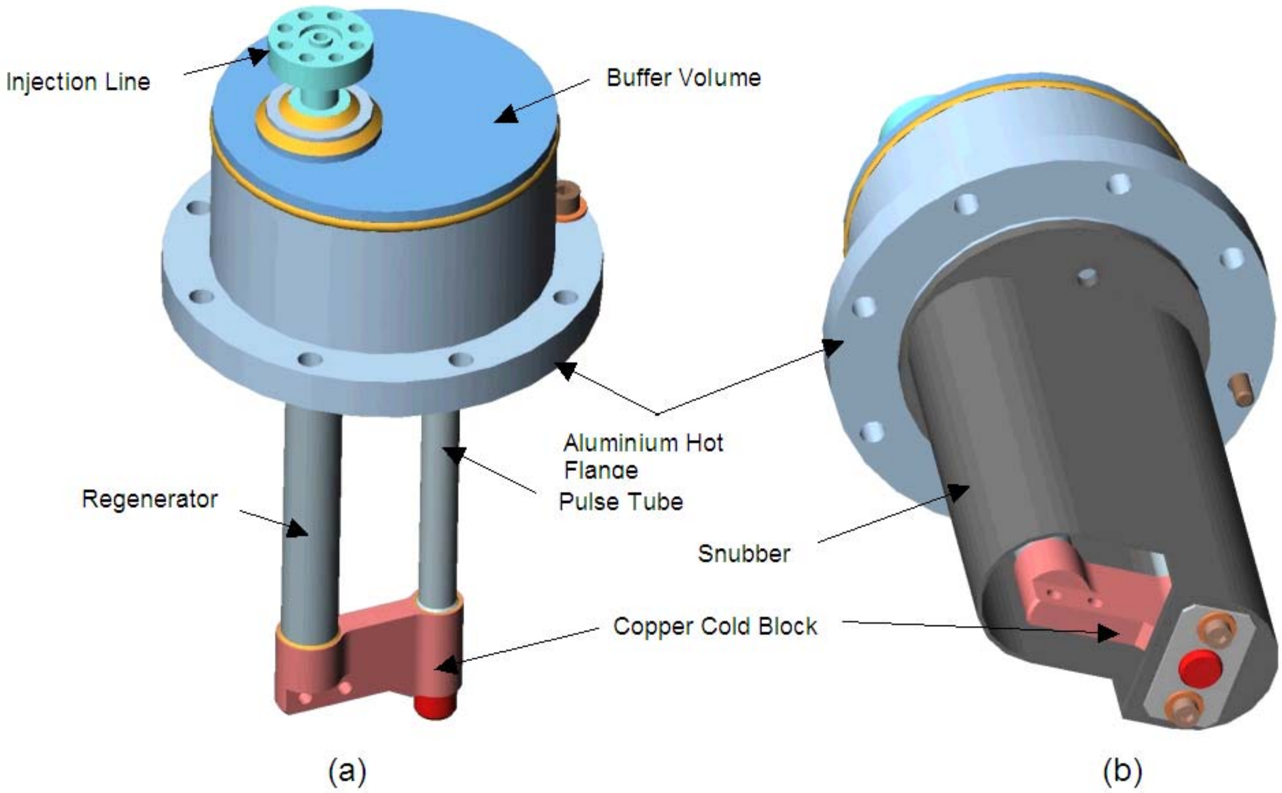

Figure 6. Preliminary design of the pulse tube cold finer Engineering Model.
(a) without snubber. (b) with snubber.

As represented in the figure 6a and 6b, the pulse tube EM will incorporate a snubber which will be used as a launch bumper stop to prevent any excessive lateral motion of both tubes and consequently to significantly reduce the mechanical stress on the tubes at the flange location. This snubber will be made of Titanium for obvious reasons of mechanical performance and density optimisation. A low conductive fibber glass part placed between the cold block and the snubber cylinder is ensuring that low parasitic heat losses are added in case of contact during operation (with loads). In normal condition, there is no contact between the snubber and the cold block of the pulse tube.

The design of the EM provides sufficient margins with respect to an internal pressure of 75 bars equivalent to 1,5 times the maximal operating pressure. The total mass of the EM pulse tube cold finger is predicted to be 700 g including the snubber.

Linear Compressor EM

The compressor design is built around a moving-magnet linear motor that drives the pistons in dual opposed configuration into the same compression chamber. The moving magnet linear motor offers big advantages over the conventional moving-coil design. This innovative concept allows the coils that are the main source of gas contamination to be placed outside the working gas. Additional advantages are the absence of flying leads and glass feed-throughs to supply current to the coils. Thus, moving magnet technology is applied in our compressor design to improve the reliability of the complete system. The main disadvantages of this configuration are the losses and the EMI which are higher than in a conventional moving-coil design.

High performance axially magnetised NdFeB magnets are used in the motor.

Flexure-bearings are used in order to have a radial clearance between the piston and the cylinder. These flexure-bearings are round discs made of spring steel, with 3 arms. With this kind of flexure bearings, a very high radial stiffness can be reached. By changing the shape, the length and the thickness of the arm, the ratio between the axial and the radial stiffness can be changed without increasing the maximum stresses in the flexures. The fatigue limit of the spring steel is 800N/mm^2. To have enough safety margin the design limit for the VonMisses stresses is set to 600N/mm^2 as presented in the figure 7 below.

The EM compressor assembly is represented in the figure 8. The coils holders are made of titanium alloy in order to reduce the eddy current losses and to combine high mechanical resistance and low density. The two compressor halves are mounted on a dedicated aluminium alloy “centre plate” that contains all the mechanical and thermal interfaces of the compressor and the two cylinders.

Bolted flanges are directly machined in the titanium alloy block of the coil holder. The gas containment is achieved by means of aluminium C-rings that provide a leakage rate of 10^{-10} mbar.litre/sec.

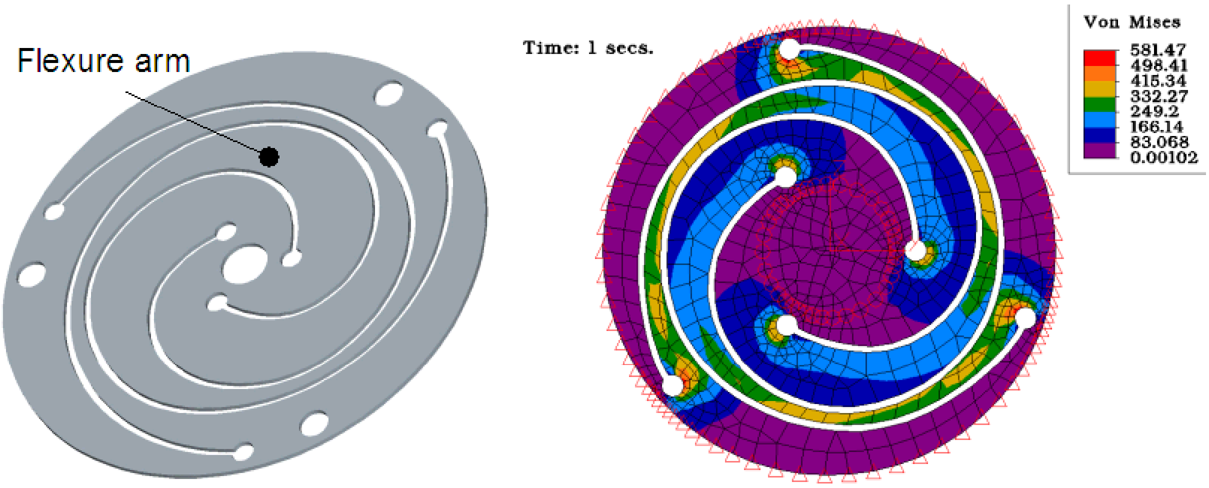

Figure 7. Flexures used in the compressor design.

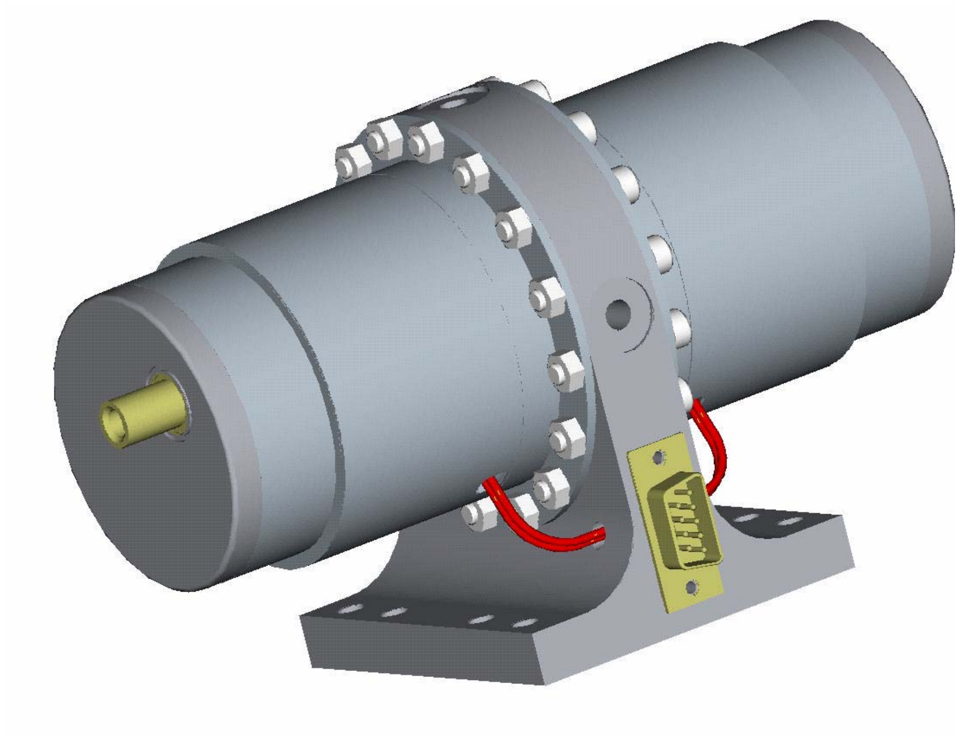

Figure 8. EM compressor design.

The outer diameter of the compressor halves is 63 mm and the total length is approximately 170 mm. The total mass of the Engineering Model compressor is predicted to be 2100 g.

The overall efficiency of the compressor has been simulated to 70% at 20°C ambient temperature.

CONCLUSIONS

A compact, lightweight and robust U-shape Miniature Pulse Tube Cooler is under design. Presently, the predicted cryogenic performance of the Engineering Model while implementing the high performance materials depicted herein are 1240 mW @ 80 K with 288 K heat rejection temperature and 43,4 Wac electrical input power (considering 70% compressor efficiency).

Some optimisation work is still going-on in order to increase the cooling capacity (pulse tube geometry) and the compressor efficiency (magnetic circuit and coils).

ACKNOWLEDGMENT

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