Thermal Testing of an EM Two-Stage Coaxial Pulse Tube Cold Finger for Earth Observation Missions

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ABSTRACT

In the framework of a Research and Technology program co-funded by the French space agency (CNES), CEA/SBT has developed a two stage coaxial pulse tube in its engineering model version (EM) that fulfills the space requirements. This cold finger has been designed, manufactured and tested at CEA/SBT. The thermal performance is presented in this paper. We tested several rejection temperatures as well as different input PV powers with a test compressor. Then, the matching of this cold finger with an EM LPTC compressor has been verified leading to a high TRL level cryocooler. In this configuration, the cryocooler provides simultaneously 3 W at 121.1 K on the first stage, and 1 W at 41.3 K on the second stage with 160 W of electrical power and a rejection temperature of 10°C. In addition, the impact of the phase shifting on the second stage has been studied by using an active phase shifter compressor and large gains on both stages have been achieved. In this configuration we managed to obtain an ultimate temperature as low as 16 K on the second stage.

This cooler is already addressing the cooling needs of detectors of most of the earth observation missions.

INTRODUCTION

Two stage coolers have been first developed to achieve lower temperatures than single stage coolers. For earth observation, two stage coolers operating in the same temperature range (50K - 80K) as single stage coolers have been identified as a promising technology. It presents several advantages and could allow cryostat design optimizations. This type of cold finger is interesting if several IR channels, operating at different temperatures, are used. The powerful first stage could also be used to cool optics, electronics or actuators that do not need to operate at the same cold temperature as the detector itself. Finally, using a two stage configuration allows the assembly of a more efficient cryostat and reduces the electrical consumption of the cryocooler. This is particularly true when redundant coolers are used. In this paper, the results of thermal characterization of an EM cold finger as well as attempts to improve its performance will be presented.

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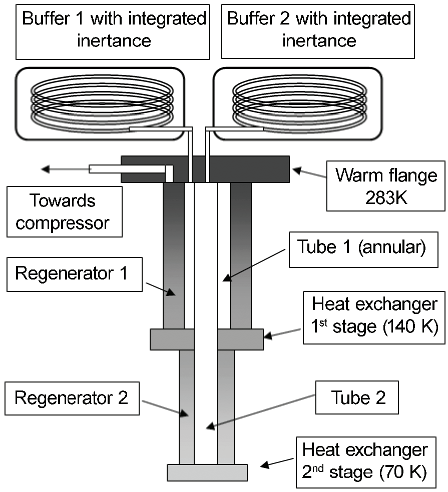


Figure 1. Schematic view of the two stage cold finger.

COLD FINGER

The two stage pulse tube cold finger presented in this paper was developed and built at CEA/SBT. It has been designed to EM standards in a coaxial configuration[1]. The specificity of the two stage coaxial version compared to a single stage coaxial version comes from the fact that the tube of the first stage is annular. The sizing of this cold finger was based on a U shape prototype (Demonstrator Model). A schematic of the two stage cold finger is presented in the Figure 1. The cold finger is presented in a CAD version and after assembly in Figure 2.

RESULTS WITH A TOOL COMPRESSOR

Test bench description

In order to have more degrees of freedom during thermal characterization, the cold finger was tested using a Thales Cryogenics maxi compressor 9710. The warm flange of the cold finger was maintained at the desired temperatures by a chiller. The cold finger was equipped with a snubber (required to withstand launch loads) on the first stage and the whole cold finger has been wrapped with multilayer insulation to decrease the thermal radiation losses from the room temperature vacuum vessel.

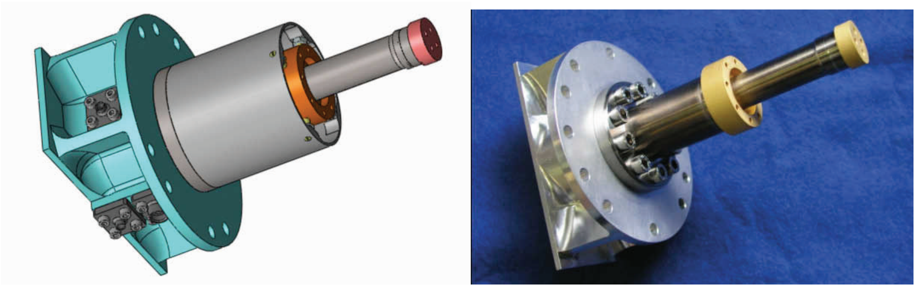


Figure 2. EM cold finger with snubber on the first stage (3D drawing) and without snubber (picture).

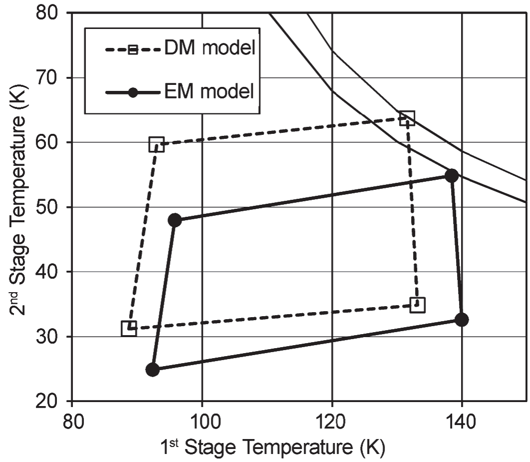


Figure 3. Comparison between the EM and the DM version - load map with 6 W and 2 W respectively on the first and second stage -120 W PV / 57.5 Hz / 30 bars / ~15°C.

Thermal test verification

The performance of the EM was checked by doing a map load, and was compared to the results obtained with the U shape prototype (DM). The map load was performed using loads of 6 W and 2 W on the first and on the second stage, respectively. Measurements are presented in Figure 3. It can be seen that the performance of the second stage is better for the EM than for the DM, whereas the opposite is true for the first stage. This behavior is attributed to the annular tube of the first stage which allows heat transfer from the first stage tube to the second stage tube.

In order to compare the results of the 2 cold fingers, it is possible to use an efficiency criterion that we have defined in a previous paper[2]. In the Figure 3, the grey curve for the DM model corresponds to coolers having the same efficiency. The difference between the 2 curves is 5%. The EM performance is about 5% higher than the DM, even if it has less adaptability to a specific need.

Effect of the rejection temperature

The effect of the rejection temperature has been investigated (Figure 4). The temperature of the warm flange has been changed using a chiller. This flange is decoupled from the vacuum vessel using a PTFE flange and the temperature of the vacuum vessel has not been regulated (laboratory temperature).

During the project, the goal has been refined and this study as well as results presented later in this paper has been done with smaller cooling powers on the first stage and second stage. It means 3 W and 1 W instead of 6W and 2 W, respectively.

There is a strong impact of the rejection temperature on the first stage temperature (2.9 K/K). This is due to the short length of the first stage (first regenerator). The second stage is less affected by the rejection temperature (10.9 K/K) thanks to the filtering effect of the first stage.

Effect of PV power

The effect of the mechanical power given to the gas has been studied. The map for (3W/1W) has been plotted in Figure 5 for various PV power. The PV power is assumed to be the total electrical power given to the compressor minus the compressor Joule losses.

As expected, the no load performance are not strongly affected which is not the case when 3 W and 1 W are applied respectively on the first and second stage of the cold finger.

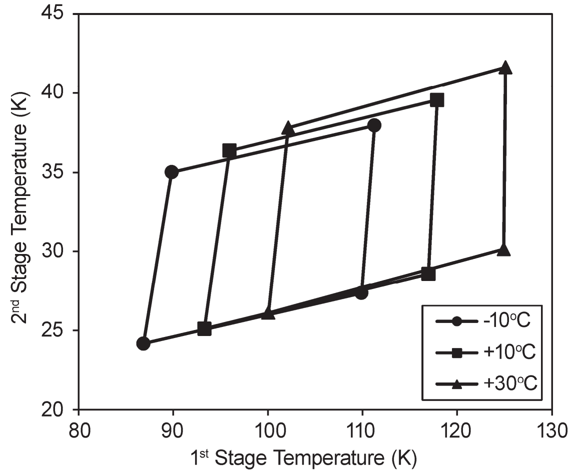


Figure 4 . Effect of the rejection temperature - load map with 3 W and 1 W respectively on the first and second stage - 120 W PV / 57.5 Hz /30 bars. Rejection temperature measured on chiller interface side.

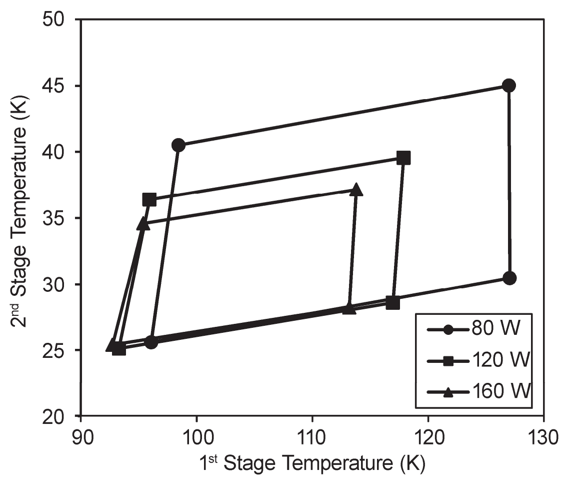


Figure 5 . Effect of the PV power: load map with 3 W and 1 W respectively on the first and second stage 57.5 Hz / 30 bars / +10°C.

RESULTS WITH A LPTC COMPRESSOR

One of the key requirements during the development of this two stage cold finger was the fact that this cold finger should be able to operate with an EM LPTC compressor. The Large Pulse Tube Cryocooler (LPTC) compressor was developed by Thales Cryogenics during an ESA Technical Research Program led by Air Liquide and devoted to the development of a LPTC[2]. This cryocooler will fly on several space programs, like the Meteosat Third Generation. The LPTC compressor will reach a high TRL level. Accordingly, the qualification efforts needed for a new cooler, made out of this compressor and the EM two stage cold finger, will be limited. The EM LPTC compressor was connected to the two stage cold finger and a load map was developed with 3 W and 1 W of cooling power on the first and on the second stage, respectively. For this test, the goal was not to measure the performance of the cold finger but the performance of the complete cooler. In order to accomplish this, the total electrical power was set to a nominal value of the LPTC cooler, i.e. 160 W. The performance obtained is presented in the Figure 6 for two different rejection temperatures.

This cooler can supply simultaneously 3 W of cooling power at 121.1 K and 1W at 41.3 K respectively on the first and on the second stage with electrical power of 160 W and a rejection temperature of 10°C. This level of performance should be able to meet most of the earth observation missions' needs.

RESULTS USING AN ACTIVE PHASE SHIFTER

Inertances are known to be limited in controlling the phase shift and can limit the performance of the pulse tube at a low temperature. In order to decrease the temperature of the second stage, the inertance of the second stage was removed and replaced by a second compressor in order to control perfectly the mass flow rate amplitude and the phase shift between the mass flow rate and the pressure in the pulse tube cold finger (see Figure 7). This mode is called "active phase shift" and is described in greater detail in a previous paper[4]. The second compressor used for the test describe here is an EM MPTC (Miniature Pulse Tube Cooler) compressor[5]. The inertance of the first stage was kept constant during the test presented below.

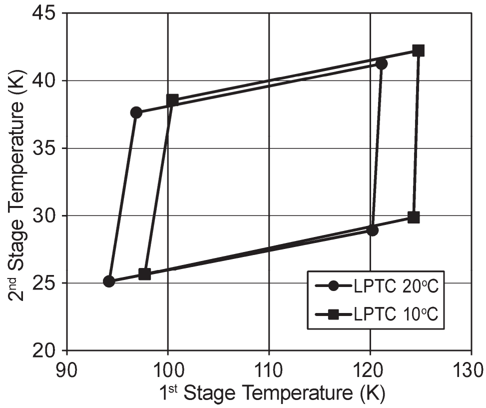


Figure 6. Performance achieved with the two stage EM cold finger connected to an EM LPTC compressor - applied load (3 W/1 W) - 57.5 Hz /30 bars / 160 W electrical power.

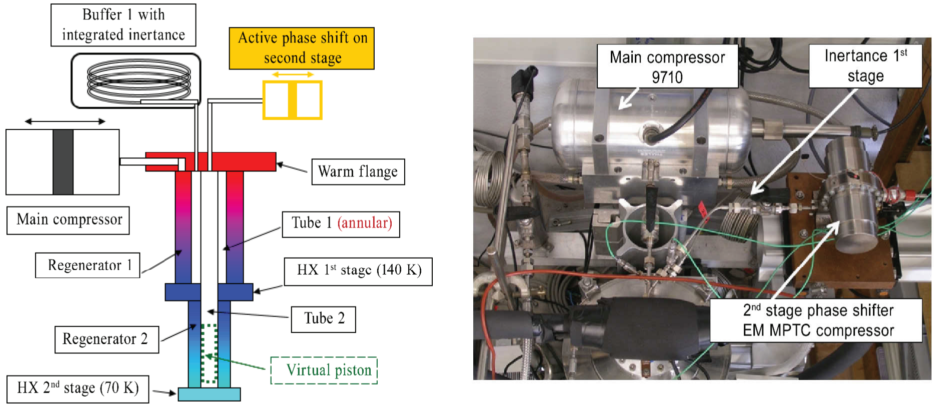


Figure 7 – Schematic of the two stage pulse tube cold finger in phase shift mode.

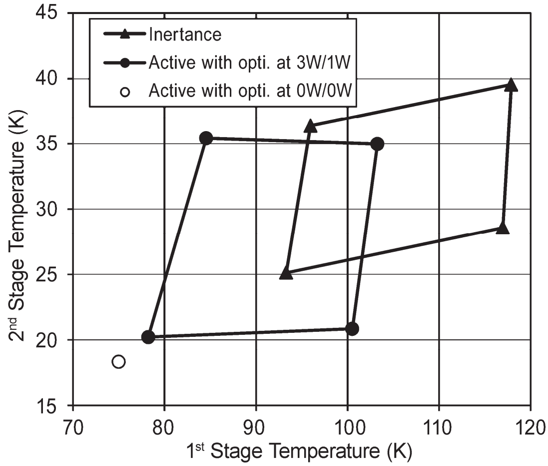


Figure 8. Performance in active phase shift mode (plain line = optimized at 3W/1W, empty circle = optimization for ultimate temperature) and in inertance mode - 120 W_{PV}, 57.5 Hz, 30 bars, 10°C.

The cold finger was tested for 120 W_{PV} and the phase shift and mass flow rate amplitude of the second compressor was optimized to deliver the best performance for 3 W and 1W applied on the first and second stage of the cold finger. The gain for the measurement with load (3W/1W) is significant. The gain on the second stage was around 5 K and the gain on the first stage is even higher, around 15 K. Such a gain on the first stage was not expected. One possible explanation is that a better phase shifting of the second stage will probably reduce the mass flow rate to this stage and the flow distribution is changed in favor of the first stage.

A full load map was done using the same setting parameters as the one found for the load case with 3W/1W (Figure 8). Then, the setting parameters for the second compressor were optimized again for the no-load case. A no-load temperature of 18 K has been achieved (empty circle).

In order to decrease the ultimate temperature, the filling pressure was reduced to 20 bars and the PV power was increase to 160 W. In this condition a no-load temperature of 16 K was achieved on the second stage.

PARASITIC HEAT LOSSES

The parasitic heat losses have been measured by a warm up method. The cold finger is still equipped with a snubber on the first stage and wrapped with MLI. When the rejection temperature is at 10°C, a loss of around 1200 mW at 110 K has been found on the first stage and around 160 mW on the second stage. By comparison, the losses measured on the single stage LPTC built in the framework of the ESA TRP had a parasitic heat loss of approximately 650 mW.

The level of losses on the first stage of the cold finger is quite high due to the short length of the first stage, but the losses on the second stage are very low and are advantageous in the cold redundancy configuration.

In the Figure 9,the cooling capacity of the EM two stage cold finger is compared to the one measured for the first EM LPTC built during the ESA TRP when the cooler is used in a cold redundant configuration. In this comparison, the cooling power delivered by the first stage is not taken into consideration. It is only used to compensate for the parasitic losses of the OFF cooler. In that sense, this is a very conservative comparison. It can be seen that the two stage cold finger has better cooling performances for temperature below 55 K than the LPTC. In the case of a cryostat using the first stage cooling power, this 55 K temperature would probably be increased significantly.

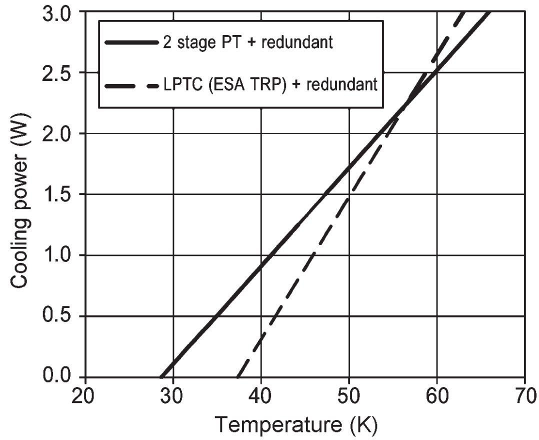
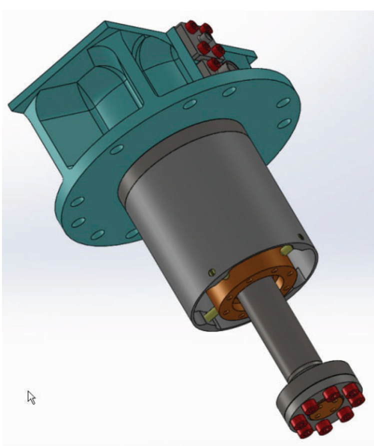


Figure 9 . Comparison of load curves for the EM two stage cold finger and the ESA TRP LPTC cold finger-160 W electrical power, 57.5 Hz, 30 bars, 10°C.

COLD FINGER DEMOUNTABLE VERSION

Once the design of an EM is frozen, it is usually difficult to evolve the design except during the qualification. In order to follow our development and to be able to implement it quickly into a high TRL cold finger, the design of a demountable coaxial version of the cold finger has been made and a prototype has been manufactured. This prototype has a demountable cold end on the second stage (Figure 10), and it is possible to change and study the regenerator of the second stage in this coaxial version, which is very close to the EM previously built.

For the first test, the regenerator of the second stage was filled with a regenerator having more surface area per unit volume. It was expected to have a better heat transfer and a worst pressure drop. The idea was that the no load temperature was more driven by the thermal losses of the regenerator than by the hydraulic losses. The results obtained in inertance mode are compared with the one obtained with the EM in Figure 11.



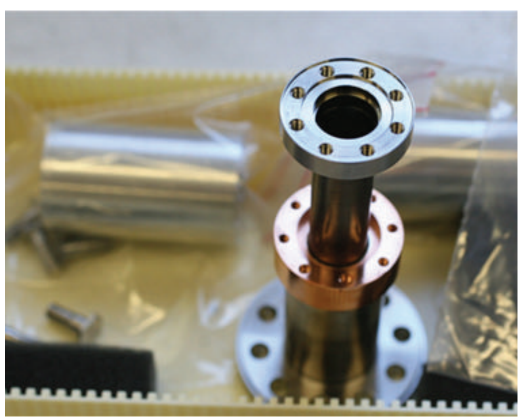


Figure 10 . CAD drawing of the dismountable coaxial cold finger (left) and assembled cold finger open with the second stage cold end removed (tube of the second stage not yet in place) (right).

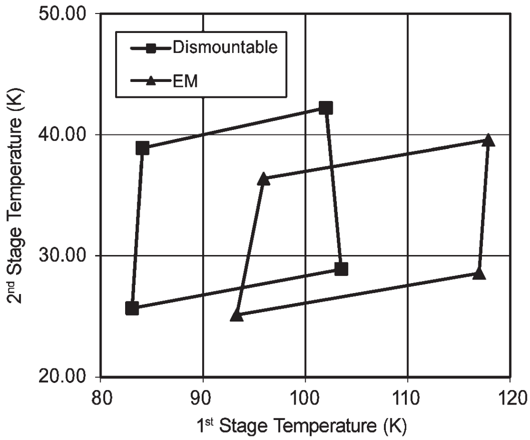


Figure 11. Comparison of the performances of the dismountable version with a new regenerator and the EM version -120 W PV, 57.5 Hz, 30 bars, 10°C-15°C.

There is no gain in the second stage temperature. The no load temperature of the second stage is not really affected, but the second stage becomes less powerful with a 3 K loss for 1W of cooling power. This is probably due to the extra pressure drop that limits the expansion and probably reduces the mass flow rate to the second stage. This is in accordance with the fact that the first stage performance strongly increases for whatever the applied load is. A gain of 15 K has been measured for the load case of 3W/1W. The gain in global efficiency is around 6% for the load case 3W/1W. It should be noticed that the absence of gain on the no load temperature of the second stage should be balanced by the fact that this cold finger with a “large” flange at the coldest part should have slightly higher parasitic heat losses. Additional tests with different regenerator fillings are foreseen in order to further increase the performances of this cold finger.

CONCLUSION

An engineering model of a two stage pulse tube cold finger featuring a coaxial arrangement has been built and has been thermally tested. It demonstrates better performances than the previous U-shape prototype version. Effect of cooling power and rejection temperature has been measured. Using an active phase shifter, a no load temperature of 16 K has been achieved even if this cold finger was not design to operate at low temperature. This cold finger has been connected with success to a LPTC compressor having a high TRL level. This cooler can supply simultaneously 3 W of cooling power at 121.1 K and 1W at 41.3 K respectively on the first and second stage using 160 W of electrical power and with a rejection temperature of 10°C. This level of performances should be able to address most of the needs for earth observation missions.

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REFERENCES

1. Charles, I., Ercolani, E., Daniel C., “Preliminary thermal testing of a high frequency two stage coaxial pulse tube for earth observation missions,” *Proceeding of the ICEC 24*, (2012), p. 207

2. Charles, I., Coynel, A., Duval J.M., Daniel C., Briet, R., Development of a Two Stage High Temperature Pulse Tube Cooler for Space Applications, *Cryocoolers 15*, ICC Press, Boulder, CO (2009), pp. 63-70

3. Trollier, T., Tanchon, J., Buquet, J., Ravex, A., Charles, I., Coynel, A., Duband, L., Ercolani, E., Guillemet, L., Mullié, J., Dam, J., Benschop, T., Linder, M., "Design of a Large Heat Lift 40 K to 80 K Pulse Tube Cryocooler for Space Applications," *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 75-82

4. Charles, I.,Golanski, L., Gauthier, A., Coynel, A., Duval, J.M., "20 K coaxial pulse tube using passive precooling," *Adv. in Cryogenic Engineering*, Vol. 53, Amer. Institute of Physics, Melville, NY (2008), pp. 887-894

5. Trollier, T., Ravex, A., Charles, I., Duband, L., Mullié, J. Bruins, P., Benschop, T., Linder, M., "Design of a miniature pulse tube cryocooler for space applications," *Adv. in Cryogenic Engineering*, Vol. 49B, Amer. Institute of Physics, Melville, NY (2004), pp. 1318-1325