Cryocooler with Novel Circulator Providing Broad Area Cooling at 90K for Spaceflight Applications

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ABSTRACT

This conceptual design of a cryocooler system for Broad Area Cooling (BAC) in spacecraft provides cryogenic circulating gas sufficient to lift 150 W of heat from a distributed tubing manifold on an actively cooled large area shield that would typically be used for reducing boil off of cryogenic propellant, while maintaining the shield temperature at 90 K.

The BAC cryocooler system consists of pulsetube cryocoolers that cool circulating gas in a separate cooling loop via conductive heat exchangers mounted to the cryocooler coldfingers. The separate cryogenic gas circulation loop is pumped by a novel circulator utilizing a pulsetube to connect an ambient temperature linear compressor to a pair of cryogenic reed valves.

The BAC cooler system design has a specific power of 15 Watt of cooler power per Watt of heat load at 90 K and a specific mass of 0.7 kg per watt of heat lifted. The cooler is a flight like system that leverages flight proven NGAS pulse tube cryocooler technology and hardware building blocks.

INTRODUCTION

This cryocooler conceptual design came out of a NASA funded study for a cryocooler system to interface with a broad area cooling tubing manifold suitable for achieving very low boil off in large cryogenic propellant storage tanks in space (Figure 1). For this conceptual design study NASA defined a load for this application as a series of parallel tubes that cool a thermal intercept shield for a cryogenic propellant tank with a parasitic pressure drop such that the pressure drop between the entrance of the supply tube and the exit of the return tube is at least 1.5 psi, and presents a total thermal load of 150 W.

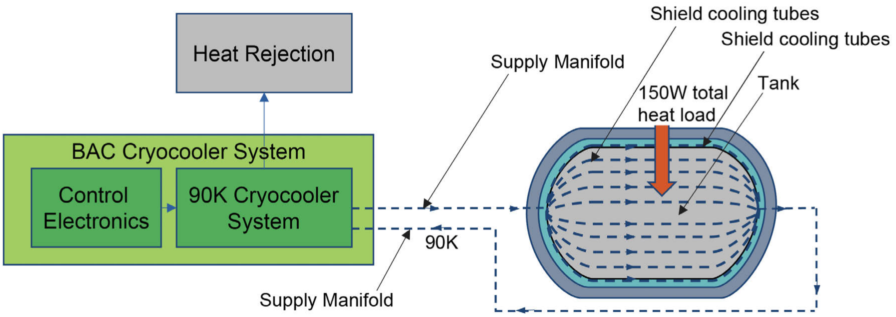

Figure 1. Functional block diagram of the BAC cryocooler System and cryogenic propellant storage tank.

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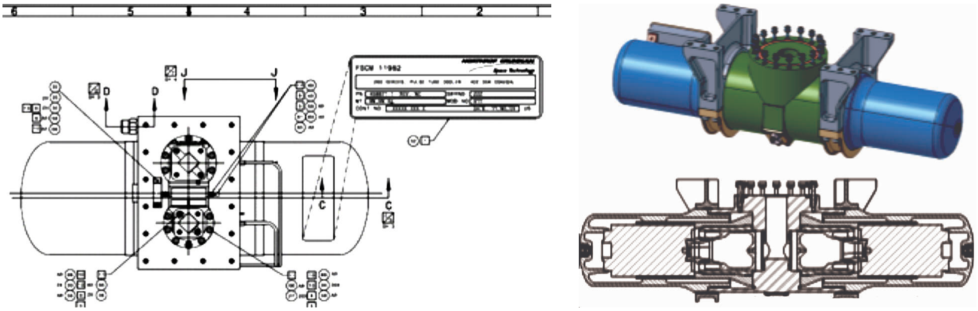


Figure 2. Key building blocks of the BAC cryocooler system
a) Left hand image 35K/85K HCC pulsetube cryocooler b) Right hand image TAPC linear alternator.

NASA programs such as Artemis, which aims to use this stored cryogenic propellant technology for a potential lunar mission within 4 years, favor the use of high Technology Readiness Level components as building blocks. Thus, we chose the high TRL6 85K HCC cooler[1] (Figure 2a) and the HEC based TAPC compressor[5,6] (Figure 2b) as the starting building blocks.

Building on previous studies for circulating cryogenic fluid for remote cooling[2,3], it was apparent that directly utilizing the cold gas from the pulse tube cryocooler by adding cold valves to the coldhead results in losses in lift which are significantly greater than if a separate pump is used. Thus this design study started with the basic approach of using a separate circulator pump and heat exchangers.

The resulting design utilizing building blocks chosen to minimize risk through maximum reuse of high TRL, high heritage, and high design maturity components is shown in Figure 3. The following sections describe the design approach and the resulting cooler design in more detail.

DESIGN APPROACH

Building on previous studies for circulating cryogenic fluid for remote cooling[2,3], it was apparent that directly utilizing the cold gas from the pulse tube cryocooler by adding cold valves to the coldhead results in losses in lift which are significantly greater than if a separate pump is used. Thus this design study started with the basic approach of using a separate circulator pump and heat exchangers.

If the separate pump requires the cryogenic gas to circulate to ambient temperature and back, then a large, heavy recuperator is need to provide thermal isolation[4]. Thus a cryogenic pump topology

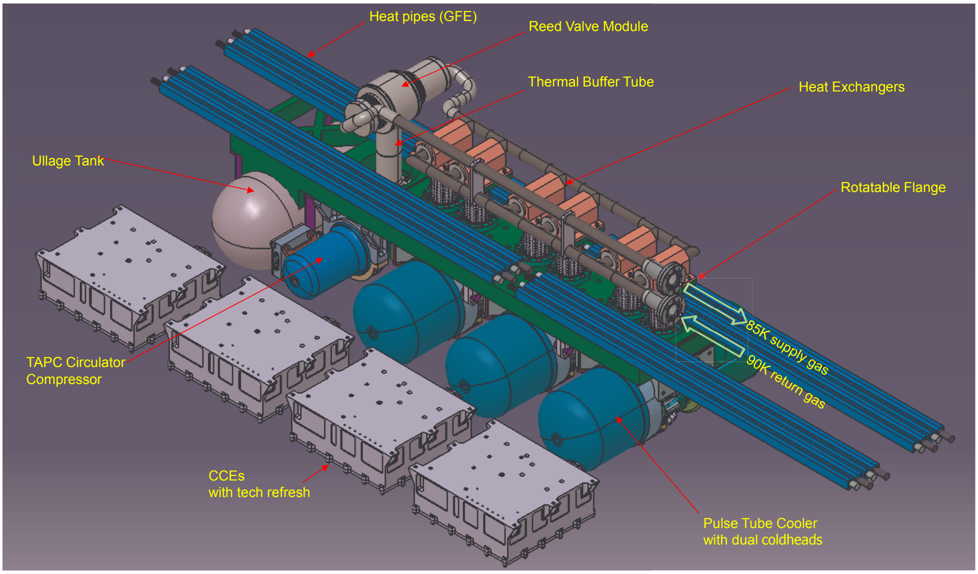


Figure 3. 90K BAC cryocooler system with circulator for broad area cooling, with key subsystems labeled.

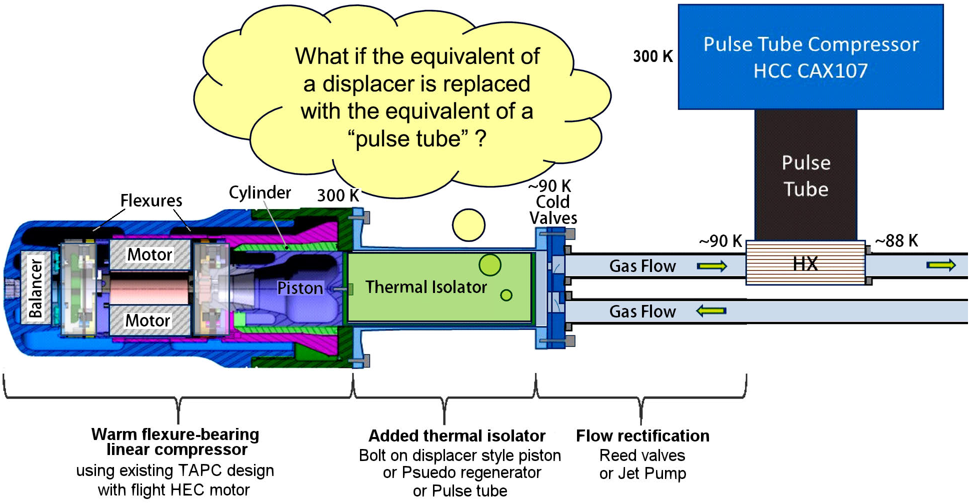


Figure 4. Initial concept for a warm compressor using a linear motor with a displacer type thermal isolator and cryogenic reed valves.

was selected for the study. An ambient temperature motor for the cryogenic pump coupled with a thermal isolation is desirable from high TRL, high reliability standpoint.

The linear flexure compressor / alternator designed for space heat engine application[5,6] (Figure 2b) is a good candidate for such an ambient temperature motor. Initial calculations showed that one piston of this compressor design has sufficient swept volume for the required volumetric flowrate.

The initial concept for thermal isolation of the compressor was to add a piston extender with low thermal conductivity and low mass, as shown in Figure 4. Conceptually this could be a thin walled hollow cylinder or G10CR or other similar material. However, this has several disadvantages; the cantilevered mass and cantilevered forces acting on the flexures, the cryogenic close tolerance seals, and the awkward configuration required to implement the desired vibrationally balanced back to back configuration. These disadvantages have some similarity to those of displacers in traditional Stirling refrigerators, which prompted the idea that a thermal buffer tube (also known as a pulse tube) could be used instead, analogous to the way that a thermal buffer tube replaces the displacer in a pulse tube cryocooler. This configuration, in the context of the overall system is illustrated in Figure 5.

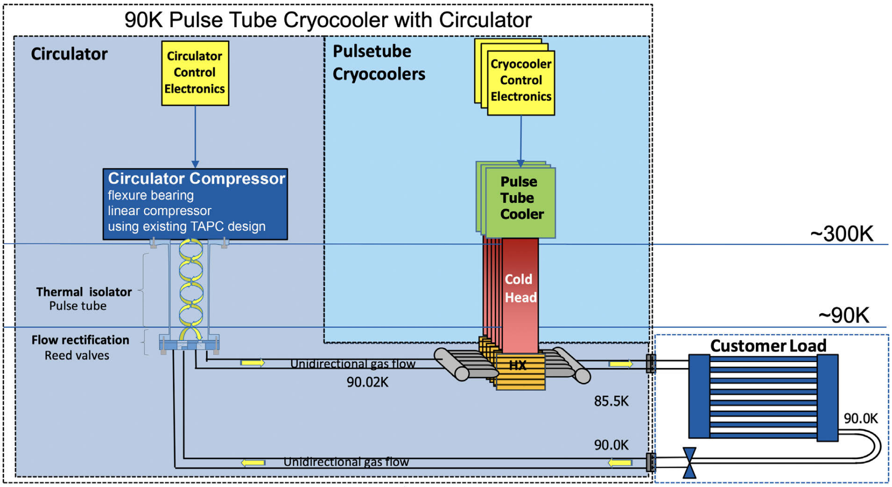


Figure 5. Schematic diagram of the cooler system and broad area cooling load using thermal buffer tube for thermal isolation of the compressor.

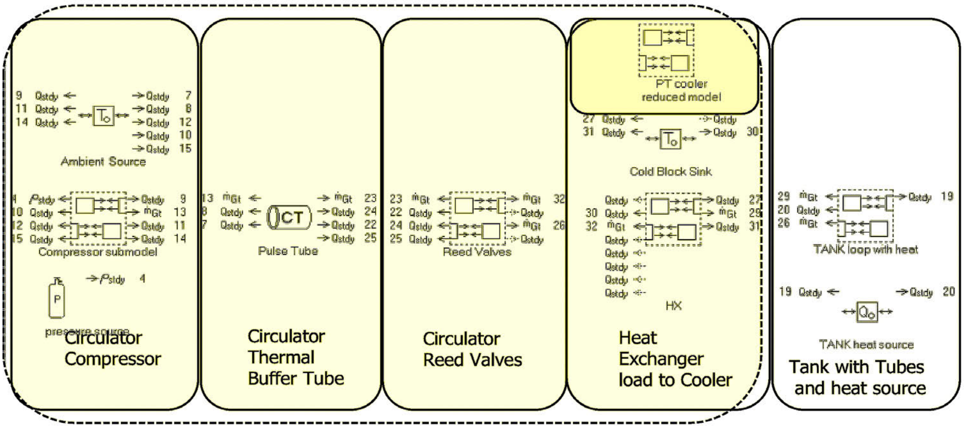


Figure 6. Top level of the SAGE model of the cooler system, along with the cooler system schematic.

The thermal buffer tube introduces its own tradeoffs and design constraints. On one hand, it must have sufficiently large volume that the tidal amplitude is small enough that convective losses are negligible, yet this necessary volume reduces the pressure amplitude per piston swept volume. It must have a sufficient aspect ratio to suppress vortices, yet have a diameter consistent with interfacing with the piston at one end and the reed valves at the other end. There is also a tendency for streaming[7] along the wall that can require a taper.

The thermal buffer tube's tradeoffs are coupled with the compressor's design constraints in terms of swept volume and frequency, and also with the opening pressure of the cryogenic reed valves and the pressure drop in the reed valves and heat exchangers. These are all influenced by the volumetric flow rate required to transport the heat from the shield to the cooler which is in turn determined by the temperature difference allowed by the power budget and the Pulse Tube (PT) cryocooler's efficiency. Thus the design attributes of the compressor, thermal buffer tube, cryogenic reed valves, heat exchangers and pulse tube cooler are coupled and need to be optimized as a coupled system.

A constrained optimization of the conceptual design was performed in SAGE[8], with constraints defined by either existing hardware attributes (e.g. component design parameters, such as the existing compressor design's stroke and bore and the existing PT cooler design's power vs temperature and lift characteristics. existing compressor and PT cooler parameters) or by constraints imposed on new components by analysis in FEA or CAD. The top level of the SAGE model is shown in Figure 6. Also comparing Figure 6 to Figure 5 illustrates how the SAGE model's structure follows the structure of the schematic. The following sections describe the cooler system components, how they are modeled in SAGE, what the key design constraints and attributes are, and what the final conceptual design is.

COOLER SUBSYSTEM

Pulse Tube Cryocooler

The pulse tube cooler is a variant of the NGAS High Capacity Cryocooler models (see Figure 2a), that were developed to high TRL on prior programs1 including the NASA JWST MIRI (Mid Infra Red Instrument) cryocooler[9]. The compressor subassembly design is unchanged for this program. The coldheads (Figure 7a) are a minor variant of the NGAS prior design part number 458871 85K coaxial pulse tube coldhead subassembly which is modified slightly to accommodate the loads and thermal interfaces of the circulator HX. The specific power vs temperature curve (Figure 7b) for the cold heads are incorporated in SAGE as a simple model of the PT cryocooler. The compressors are designed for two coaxial coldheads. They were previously configured as a parallel 2 stage cooler, and are reconfigured for this application to have two parallel 95 K coaxial coldheads per compressor. Three compressors, with a total of six coldheads are used for lifting the 150W BAC load plus the thermal loads from the circulator losses.

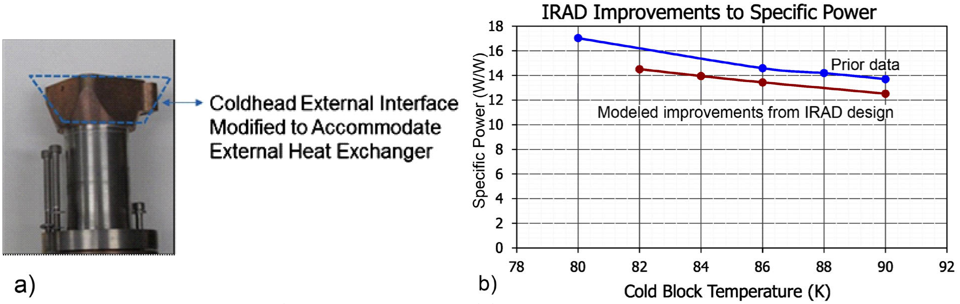


Figure 7. 85K Coaxial cold head a), specific power cold head on HCC compressor b)

Heat Exchangers

The heat transported from the BAC shield load to the pulse tube cryocoolers is removed by gas-to-solid heat exchangers. One heat exchanger is mounted onto each of the pulse tube cryocooler coldheads. The heat exchangers are manifolded in parallel, each with 1/6 of the total mass flow and 1/6 of the total heat load. The heat exchangers, Figure 8, are made from a block of Oxygen Free High Conductivity (OFHC) copper with coarse mesh copper screens inserted, using design and construction that is typical for NGAS space cryocoolers. These are incorporated into the SAGE model using anchored models from prior NGAS coldheads. The heat exchangers are highly efficient, with less than 0.1 K temperature from wall to gas, and less than a 0.08 psi pressure drop. The heat exchangers have a bolted interface to the coldheads. The thermal connection of each heat exchanger to each cold block is an Indium / Copper bolted interface, typical of space cryocooler coldblock interfaces, which results in <0.1 K delta T at rated heat lift, based on published measurements[9]. The equivalent thermal resistance is incorporated in the SAGE model as a lumped thermal resistance.

The manifold that connects the heat exchangers is made of custom Invar tubing fittings. Invar has a thermal contraction from 295 K to 90 K that is less than 1/7th that of steel or copper. This results in acceptably low stresses on the coaxial coldheads that connect the 295K compressor to the 90 K manifold. The manifold tubing length and inner diameters is included in the SAGE model.

Circulator Compressor

The compressor for the circulator is based on the TAPC alternator (NGAS part number E344350) previously developed for a NASA GRC heat engine application. This compressor has the requisite swept volume and power capacity. The motors and flexures in this compressor are the same as in the TRL9 heritage High Efficiency Cryocooler (HEC) and the TRL8 JWST MIRI Joule-Thomson compressor. The CDR level, released drawings for EM TAPC are shown in Figure 2b.

The compressor for this application does not need several of the features of the TAPC heat engine (such as the jet pump in the centerplate), so those have been removed. In this application, unlike the TAPC application, the operating temperature of the compressor is same as the heritage cryocooler from which it was derived, so unlike the TAPC application there is no need for any change to the heritage materials. The compressor for this application is at a mean pressure of approximately 500 psi during operation, but the pressure increases to approximately 1,000 psi when the system is off and at room temperature. The TAPC compressor pressure vessel was designed for 750 psi operation at very high temperatures, thus only minor modifications to wall thickness are needed to accommodate 1,000 psi at room temperature.

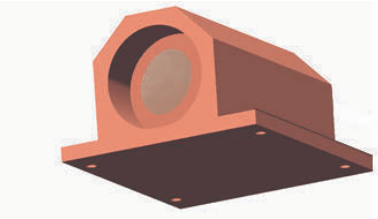
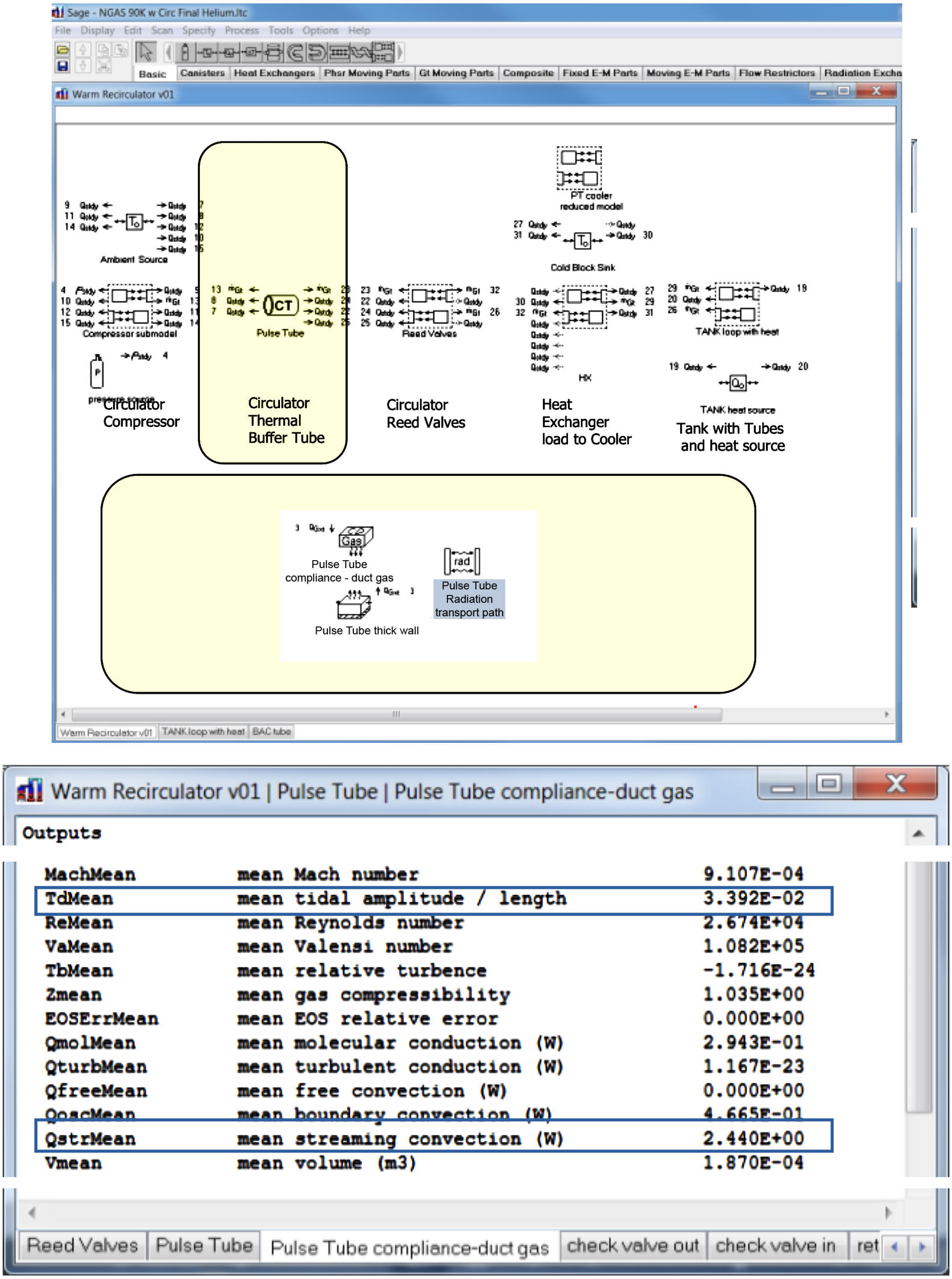


Figure 8. Heat exchanger, one of six in parallel, showing internal screen pack and bolted interface to coldhead.



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Outputs

  MachMean          mean Mach number                        9.107E-04
  TdMean            mean tidal amplitude / length           3.392E-02
  ReMean            mean Reynolds number                    2.674E+04
  VaMean            mean Valensi number                     1.082E+05
  TbMean            mean relative turbence                 -1.716E-24
  Zmean             mean gas compressibility                1.035E+00
  EOSErrMean        mean EOS relative error                 0.000E+00
  QmolMean          mean molecular conduction (W)           2.943E-01
  QturbMean         mean turbulent conduction (W)           1.167E-23
  QfreeMean         mean free convection (W)                0.000E+00
  QoscMean          mean boundary convection (W)            4.665E-01
  QstrMean          mean streaming convection (W)           2.440E+00
  Vmean             mean volume (m3)                        1.870E-04
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Figure 9. Thermal buffer tube model in SAGE, with key performance attributes.

Thermal Buffer Tube

The ideal thermal buffer tube (also known as a pulse tube) transmits acoustic power adiabatically. It is an empty tube with internal dimensions that ensure that the oscillating gas displacement amplitude is small relative to the tube length. This ensures that the gas transport of heat from one end to the other is primarily by diffusion, not by advection or convection. The pulse tube is a standard feature in our heritage coolers. The SAGE model of the thermal buffer tube (Figure 9) is based on the models from prior NGAS space cryocoolers. The inner diameter and length of the pulse

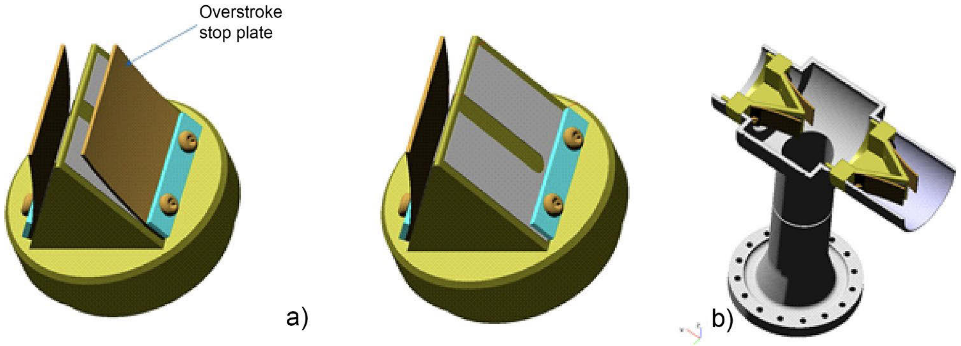

Figure 10. Reed valves a) reed valves b) reed valve module with suction and discharge valves mounted onto Thermal Buffer Tube.

tube were optimized as part of the overall system optimization. The aspect ratio was constrained based on our prior pulse tube (thermal buffer tube) experience, and the volume was constrained to maintain a low tidal amplitude, and still maintain a defined stroke margin in the compressor. The wall thickness was constrained to meet the pressure design requirement. The design was limited to a straight (non tapered) tube for simplicity sake. The objective function, defined at the cooler system level, minimized the total electrical power needed. This optimization resulted in a Thermal Buffer Tube with a tidal amplitude less than 5%, and aspect ratio of three, while maintaining a stroke amplitude in the compressor slightly less than 50 % (which is the desired stroke margin at this design phase). The use of a non-tapered wall resulted in modeled steaming parasitic heat load of less than 3W (Figure 9), which was considered acceptable in the context of the 150W lift.

Reed Valves

NGAS has prior experience with reed valves coupled to compressors to provide a unidirectional flow of gas, both at room temperature[10,11] and at cryogenic temperatures[2,3].

The reed valves' size for this program was guided by the output of the SAGE models. The requirements for the reed design were driven not just by the volumetric flow rate and pressure consideration, but also the fact that the reeds should be deigned to have infinite design life. The key requirements flowed to the reed design were:

- Lift: The reed must have a port area and a lift sufficient to achieve the effective flow area defined by the Sage model.
- Impact velocity: The reed impact velocity must be at or below industry practice and have result in impact energy appropriate for cryogenic service[12,13].
- 1st mode frequency: The reed must have a first mode frequency that is at least 3 times higher than the compressor's driving frequency.
- Root Stress: The root stress must be below the infinite life endurance limit of the reed material[12] with sufficient safety margin.

The initial designs were done analytically in Mathcad and then verified with finite element analysis (FEA) in NX CAE. Each valve has four ports and four reeds angled on a prismatic surface (Figure 10a) The suction and exhaust valves are mounted in to a cylindrical module at the end of the thermal buffer tube (Figure 10b)

In this configuration, the port holes are rectangular and a pair of reeds are created from a sheet of thin, hardened stainless steel. This allows each reed to be smaller and therefore have a higher natural frequency. It also provides a flow pattern with the least likelihood of disturbing the planar flow needed for proper operation of the pulse tube. Optimized parameters of this hole and reed setup that met the requirements above were incorporated into the design and the SAGE model.

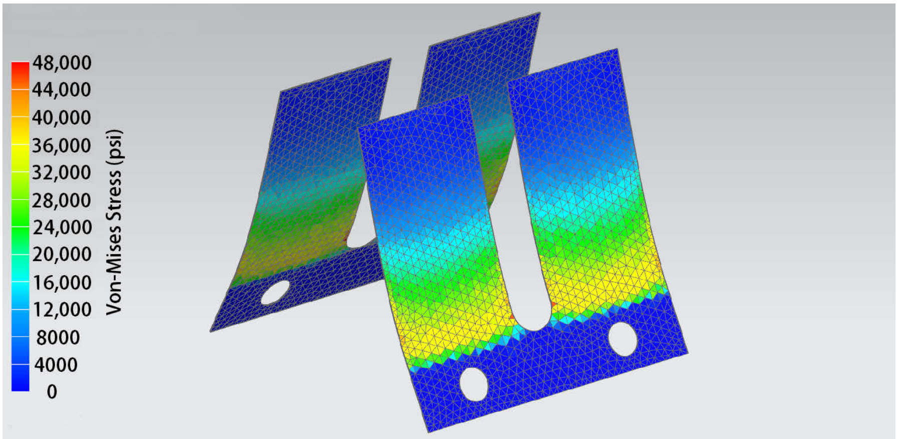

Figure 11. Stress in Reed valves is consistent with design intent.

The reed valve material is an industry standard reed valve steel, Sandvik 7C27Mo2. A FEA stress simulation of reeds at their maximum deflection was used to verify design margin. The maximum stress in the reeds (Figure 11) is well below the Sandvik published endurance limit[12]. The stress is sufficiently below the endurance limits to ensure infinite life relative to fatigue in bending. Sandvik 7C27Mo2 has been characterized and has published data at cryogenic temperatures by the manufacturer. The design has orders of magnitude of margin relative to cryogenic impact energy based on Sandvik design guidelines[12].

PARASITIC HEAT LOADS DISCUSSION

There are three sources of parasitic heat loads; conduction from the environment, external radiation, and internally generated heat loads from the circulator.

The 90K cooler's circulator hardware is completely supported by the cooler itself, so there are no external conduction loads. The coolers own internal conduction loads are accounted for in their performance.

The radiant loads are low due to the low surface area and use of high performance MLI such as Quest Thermal IMLI (Integrated Multilayer Insulation)[14], which can achieve 0.4 W/m^2 at 90K in a 295 K environment. Radiant loads are only approximately 0.3 W out of 150 W, which were considered acceptable and incorporated in to the SAGE model.

Internally generated heat loads (in addition to those imposed on the broad area cooling tubes) consist of the following:

- Heat generated in pumping the working gas through the specified 1.5 psi pressure drop in the Broad Area cooling tubes. Although technically not a cooler loss, this heat must be lifted by the cooler and was considered to be above the specified BAC load of 150 W.
- Heat generated and/or conducted within the cooler is comprised of the following contributions

– Heat conduction in the thermal buffer tube walls

– Radiant load within in the pulse tube

– Heat conduction in the thermal buffer tubes helium (diffusion)

– Heat advection in the thermal buffer tubes helium (oscillating gas displacement)

– Pressure drop in the reed valves

– Pressure drop in the heat exchangers

– Heat generated in the specified 1.5 psi pressure drop of the BAC

These loads are dominated by the thermal buffer tube heat leaks, predominantly advection and streaming.

Part of the parametric optimization in this study is the minimization of these internally generated heat loads. The optimized design has approximately 12 W of internally generated loads that are lifted by the pulse tube cryocoolers, as well as the 150 W of BAC load.

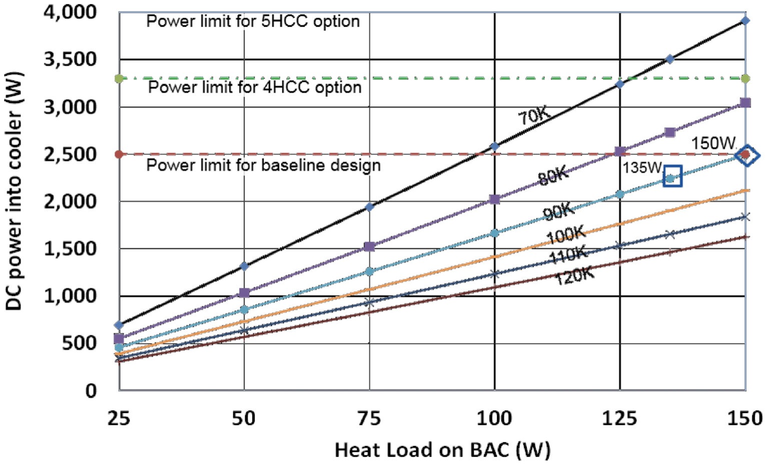

Figure 12. Total power vs BAC load for temperatures from 70K to 120K, using helium gas in the circulator

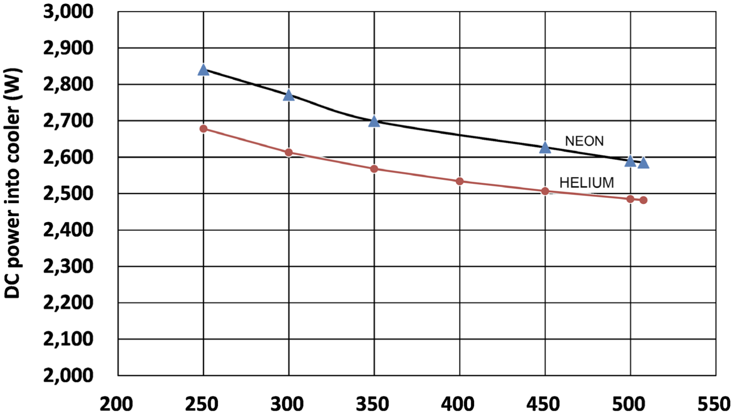

Figure 13. Total DC Power required to lift 150 W heat load at 90 K vs operating pressure, comparing helium vs neon as the circulator gas.

PERFORMANCE SUMMARY

The performance of the cryocooler, when connected to the specified Broad Area Cooling loop with its specified 1.5 psi pressure drop was estimated using the SAGE model. Figure 12 shows the performance with helium used as the circulation gas in terms of the DC power into the cooler electronics as a function of the BAC load temperature and the BAC load.

The effect of the working pressure (i.e. the pressure with the system at is nominal operating temperatures) of the circulation gas on the DC power required to lift 150 W at 90 K is shown in Figure 13. The cooler can also use neon as the circulating gas with no change to the design, but with a minor performance penalty of about 4%. The comparison of the DC power required to lift 150 W thermal load at 90 K as a function of fill pressure is shown in Figure 13.

The mass of the cryocooler subsystem (PT Cryocooler, circulator, and drive electronics), is 100 kg. The approximate envelope of the cooler subsystem is 42 cm wide by 42 cm tall by 90 cm long.

CONCLUSIONS

The conceptual preliminary design for a Broad Area Cryocooler that lifts 150 W heat load at 90 K is presented. The design meets the key requirements and is based on high TRL building blocks which provide a path to flight.

ACKNOWLEDGMENTS

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