Development of a Cryocooler to Provide Zero Boil-Off of a Cryogenic Propellant Tank

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ABSTRACT

Lockheed Martin has been developing advanced technology to provide cooling of a cryogenic propellant tank in order to achieve zero boil-off during orbital storage periods. Present systems for long duration flights show large amounts of propellant loss due to parasitic heat loads. A single-stage Pulse Tube cryocooler has been integrated with a cryogenic methane tank. The cryocooler provides a flow loop of cold gas that circulates in the storage tank and is used to absorb the parasitic heat load, thus allowing the tank to remain non-vented. The cryocooler is located at a distance from the tank, thus requiring a remote cooling loop.

The remote cooling loop uses the same working gas as the pulse tube. This flow loop is driven by the same compressor used to provide the pressure wave to the pulse tube cold head, an approach that adds very little complexity to the overall system. The flow loop utilizes steady unidirectional (DC) flow to provide cooling at temperatures near 110 K at the remote cooling location. All cooling is provided by the pulse tube cooler, so that the remote cooling mechanism is forced convection.

This paper describes the results from a flow loop developed and tested on a 635-liter cryogenic methane tank as a technology demonstrator. The flow loop, driven by a pulse tube cooler, delivered cold helium gas to and from the remote location to remove the parasitic heat load on the storage tank.

INTRODUCTION

Numerous future propulsion systems will utilize cryogenic propellants to improve performance. While the specific impulse is greatly increased over storable propellants, long duration missions can result in large amounts of propellant boil-off due to parasitic heat loads from the warm environment into the cold propellant tanks. Numerous studies[1] have been conducted pointing out the overall system benefits from reduction of or elimination of this boil-off by refrigeration means. Since mechanical cryocoolers have now been established as high reliability systems,[2] they represent a viable means to eliminate or reduce this boil-off. There are numerous approaches to employ cryocoolers for reduced boil-off. The optimum approach is system specific. These techniques include direct contact of the cryocooler cold tip with the tank wall, employment of a circulation loop (this paper) to distribute the cooling over large surface areas or multiple tanks, or the employment of various Joule-Thomson approaches.

In these approaches, a key consideration is to eliminate or reduce the temperature gradients in the propellant due to stratification, which increases tank pressure and can lead to pump cavitation. One technique to achieve this is to distribute the cooling over large areas—for example, over the propellant tank wall or internal heat exchangers to provide cooling at the optimum location. This system is described in this paper.

APPROACH

In order to achieve cooling at a location remote from the pulse tube coldhead, a flow loop was added to an existing cryocooler. The gas in the flow loop is cooled by the cryocooler and routed to the remote location where cooling is required. This flow loop operates by withdrawing a small quantity of the helium working gas from the compressor during each pressure cycle.

This gas passes through a reed valve which converts the periodic (AC) flow to a continuous (DC) flow stream. The DC flow passes through a counterflow recuperator and then through a heat exchanger on the pulse tube cold tip which cools it below 110K (suitable for liquid methane or liquid oxygen). The flow then continues several meters to the propellant tank where it removes heat, passes through the recuperator again, through a second reed valve, and flows back into the compressor. The average pressure in this flow stream is approximately the average pressure in the compressor, while the pressure head driving the DC flow is approximately twice the AC pressure amplitude in the compressor. The flow resistance of the recuperator and remote lines is typically quite small, requiring the use of a restrictive valve or capillary to limit the DC flow to the optimum value (which is determined by a comprehensive model of the entire system). Effectively, the main compressor used for the cryocooler also acts as a circulator; a schematic is shown in Figure 1. This approach is also applicable to remote cooling of instruments.[3] Since the propellant tank is cooled by enthalpy change in the helium gas, a temperature difference between the cold head and gas exiting the tank results, leading to a performance loss.

CRYOCOOLER

The cryocooler utilized has demonstrated 30 W of cooling at 95 K for an input power of 300 W, leading to a very low specific power of 10 W/W. The coldhead is an in-line single-stage pulse tube that was developed under Independent Research and Development (IRAD) funding in 1997 and is shown in Figure 2.

The compressor is our MAXI size, an intermediate size from our series of LM-ATC developed linear flexure-bearing clearance seal compressors shown in Figure 3. The MAXI compressor provides a range of swept volumes from 10 to 22 cm^3. All of our LM-ATC compressors use the moving magnet design, favored because it places the motor coil outside the working gas space, eliminating the coil epoxy (the primary source of contamination) from the gas space, eliminating electrical feed-throughs into the gas space, and eliminating flexing electrical leads.

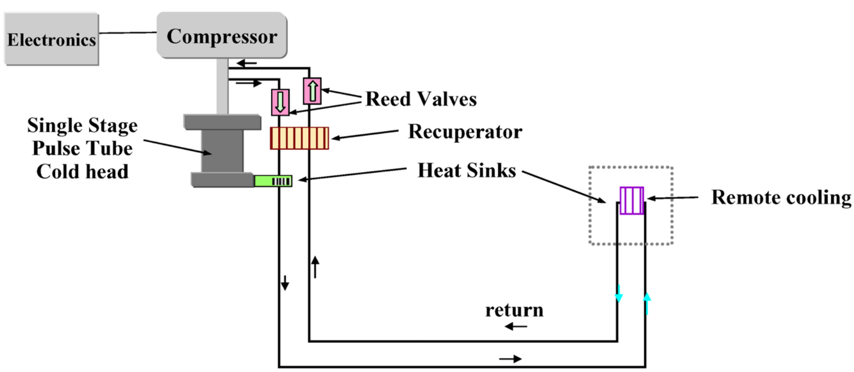

Figure 1. LM-ATC approach to remote cooling.

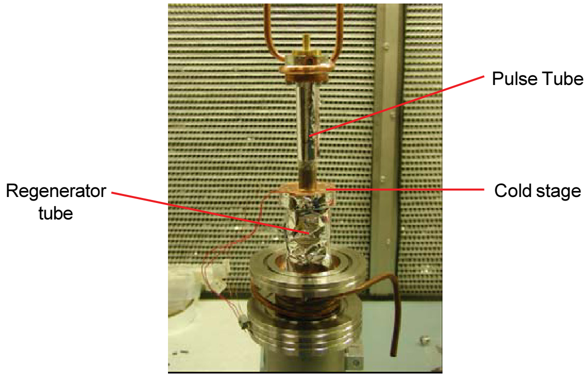

Figure 2. LM-ATC developed in-line single-stage pulse tube.

Figure 3 shows the power capability of both the M3 compressor and the advanced M5 compressor. The compressor used in this test has an M3 motor.

EFFECT OF FLOW LOOP HEAT EXCHANGER EFFICIENCIES ON PERFORMANCE

The performance of this type of system is primarily driven by the effectivenesses of the flow loop recuperator, the cold head and remote tank heat sinks, and the parasitic losses on the flow lines. Inefficiencies inherent in these components require the cryocooler to operate at higher input power and a lower coldhead temperature to compensate.

The parasitic losses of the lines arise from conductive heat load through the mechanical supports and radiative heat load from the warm environment. The primary issue to keep the radiative loads low is to control the degradation of the emittance of the lines due to gas freezing onto the lines.

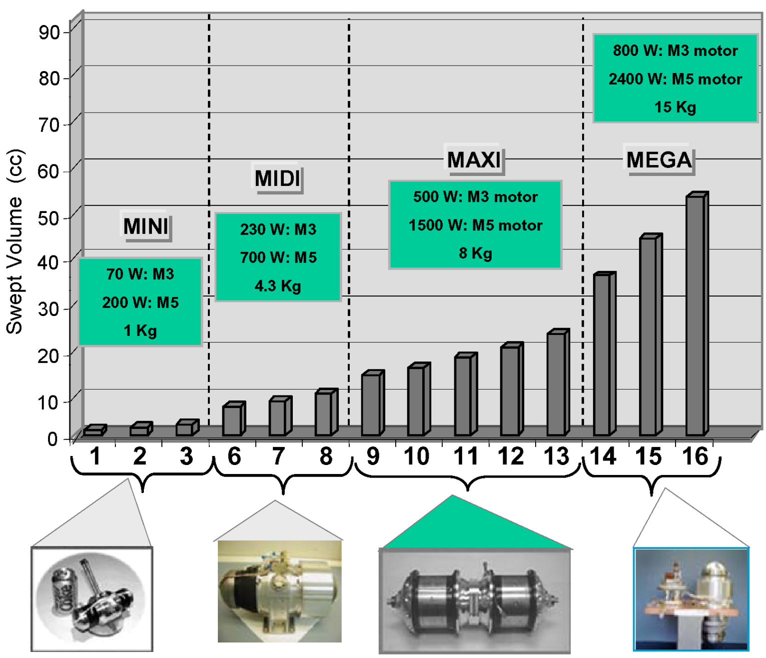

Figure 3. LM-ATC developed linear flexure-bearing clearance seal compressors; the propellant storage demonstration test utilized a MAXI M3 compressor.

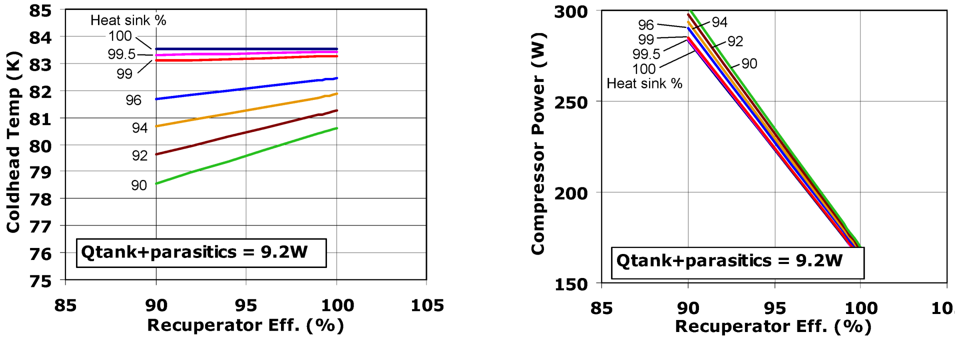

Figure 4. Effect of heat exchanger efficiencies on performance.

A recuperator effectiveness of less than 100% leads to less precooling of the gas prior to the cold head heat sink; this results in higher cooling required at the coldhead and thus more input power. Similarly, inefficiencies inherent in the heat sinks at the cold head and the tank result in having to operate the cold head at a lower temperature, which also requires higher input power.

Figure 4 shows the results of a simple analysis quantifying the effects for a case where the total heat load on the remote line including the lift at the tank is 9.2 W and the flow rate is 67 mg/s, typical of the system under test.

The recuperator used in this test was a simple tube-in-tube geometry. Based on instrumentation data taken during the testing, the measured effectiveness of the recuperator was 97.5%. The measured effectiveness of the heat sinks was greater than 99%.

REMOTE COOLING PERFORMANCE

The testing was divided into two phases. In the first phase, the cooler was tested by itself with a simulated tank. In this test, the gas passed thru a heat exchanger with a heater to simulate the tank with the objective of getting performance data associated with the remote flow loop. In the second phase, the cooler was integrated with a full scale methane propellant tank. The objectives of this latter test were to reveal and investigate issues associated with the storage and use of methane for propulsion and integration of a cryocooler with a storage tank loaded with methane. In this test, the gas passed thru a heat exchanger inside the methane tank.

Figure 5 shows the configuration of the cryocooler and associated flow loop installed on a pallet. This configuration was used for both the test of the cryocooler by itself and the test when integrated with the methane tank.

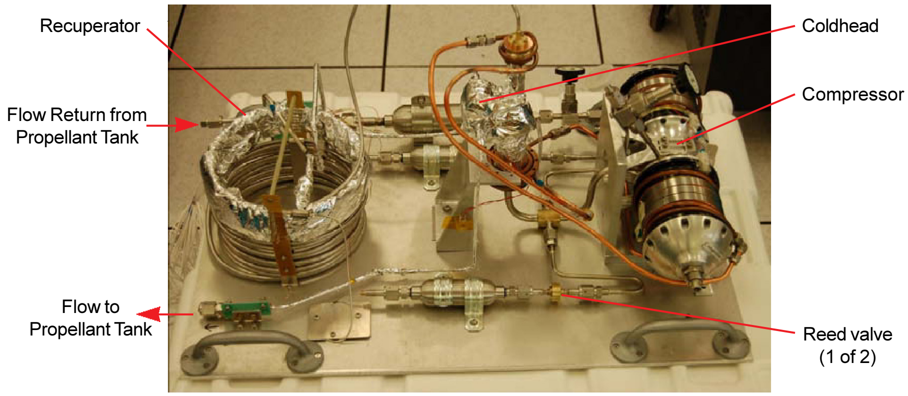

Figure 5. Configuration of cryocooler and remote flow loop on a pallet

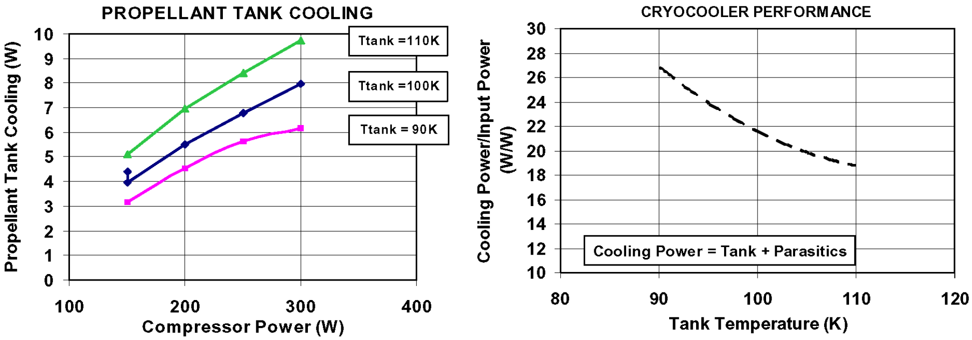

Figure 6. Performance results of the cryocooler/remote flow loop test

The performance data taken during the cryocooler test with a simulated tank are shown in Figure 6. Tests were performed over a range of 150 to 300 W input power while cooling remotely at a temperature range of 90 – 110 K. The results showed successful operation of the remote flow loop where we successfully lifted 3 to 10 W remotely over the range of power and tank temperature. During these tests the coldhead operated between 68 K and 90 K. The input power and parasitic heat loads were higher then expected, and this is being investigated to better understand the losses.

INTEGRATION WITH FULL SCALE METHANE PROPELLANT TANK

Figure 7 shows the cryocooler and flow loop integrated with the methane tank. The cryocooler pallet was installed on the deck below the tank. This deck also included other hardware including propulsion hardware being evaluated in association with the objective of this test program. During this test, the tank was loaded with liquid methane at 110 K.

SUMMARY

Preliminary results were obtained for a system to reduce or eliminate propellant boil-off. The system provides benefits by distributing the cooling over a large area so that stratification effects can be controlled or eliminated. Since the system provides cooling by absorbing the propellant heat input by warming the cold helium flow loop gas, there are some losses that are not present in a

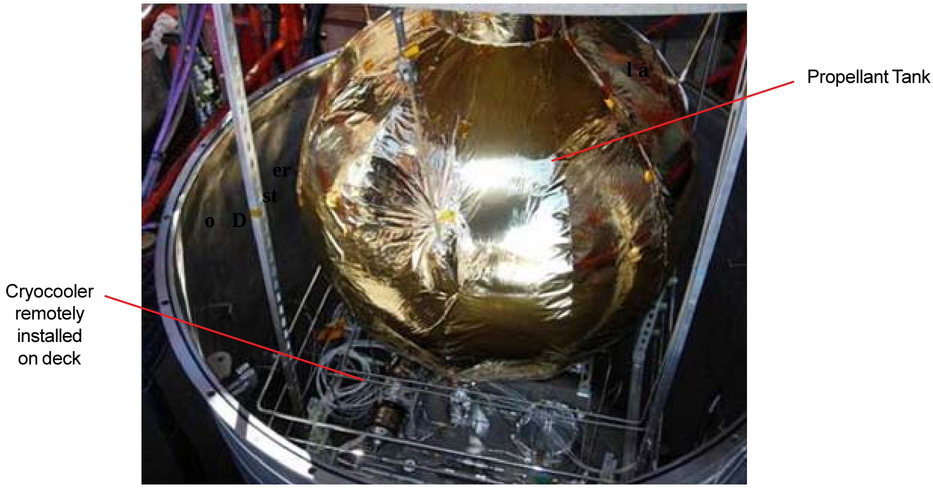

Figure 7. Cryocooler/Remote flow loop integrated with 635 liter methane tank

system that cools the tank directly by the cryocooler cold tip. A system trade study must be conducted to optimize a system which includes effects of propellant stratification and other approaches. Additional development will be required to find the optimum operating parameters of the system and to understand and minimize the losses in the flow loop.

ACKNOWLEDGMENT

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