A Study of the CryoTel® DS 1.5 Cryocooler for Higher Cooling Capacity

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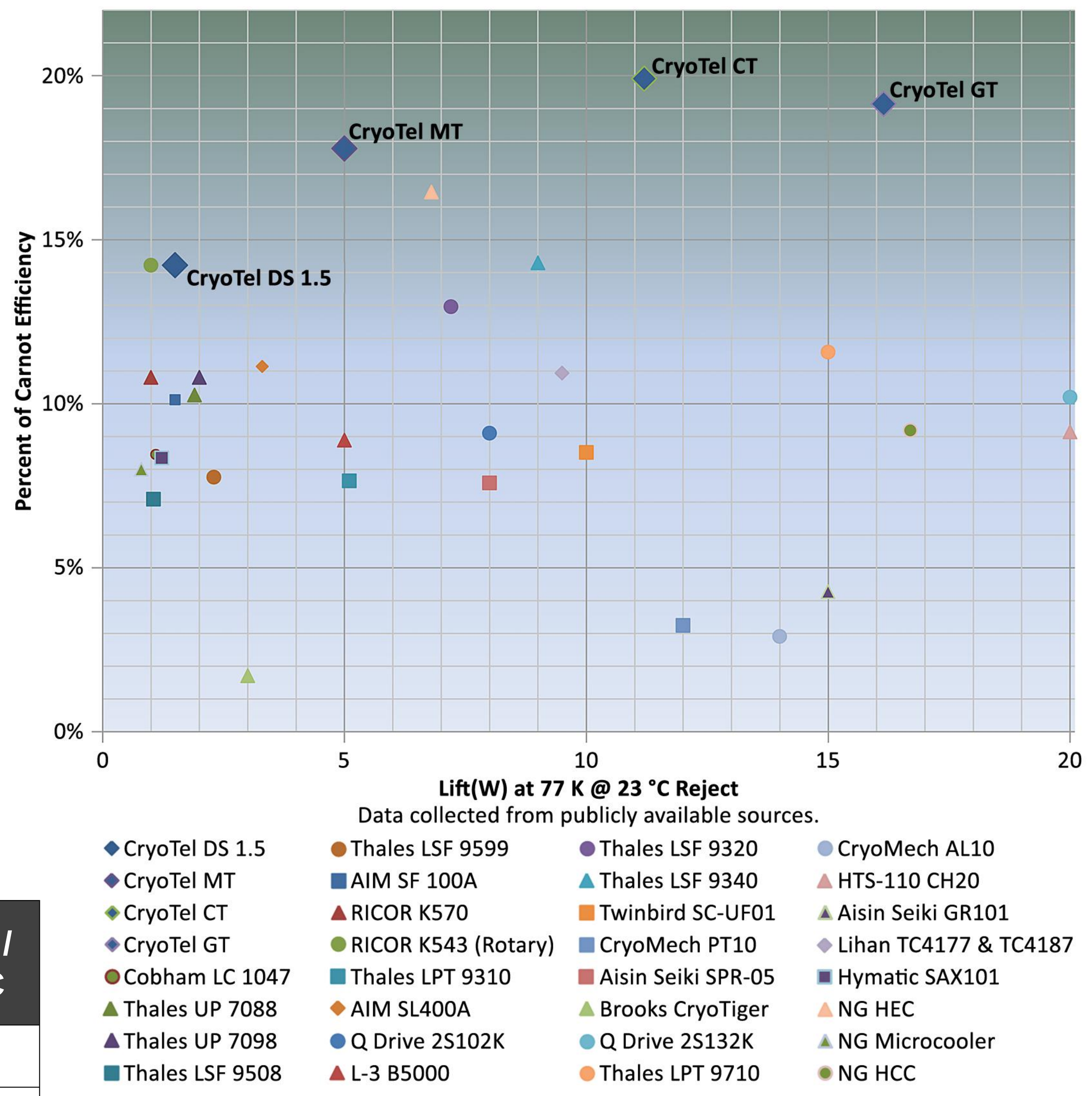
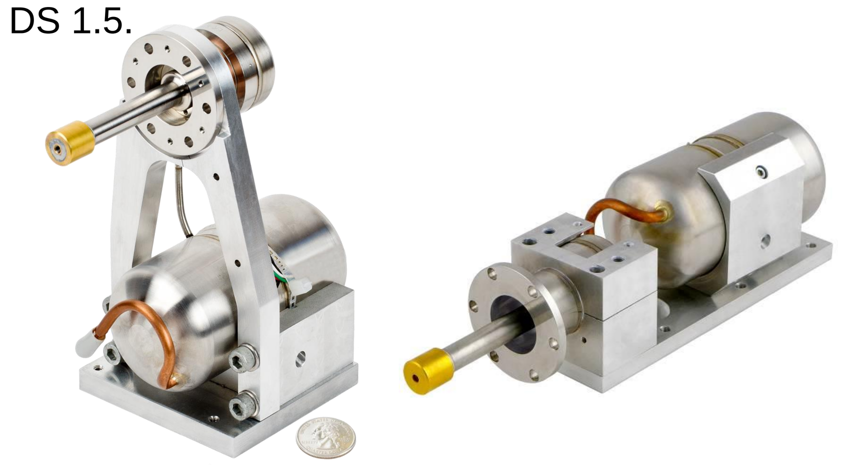
INTRODUCTION

The CryoTel® DS 1.5 is a split type Stirling cryocooler which was developed by Sunpower for systems requiring compact size, high efficiency, and high reliability. The DS 1.5 has a **nominal lift of 1.5 watts at 77 K with 30 watts of input power**. The cooler design includes gas bearings on the pistons and displacer for non-contact operation, and achieves low vibration by using dual-opposed pistons inside the wave generator, and a passive balancer on the cold head to offset the displacer motion. The efficiency of the **DS 1.5 is ranked highly compared to other cryocoolers at 14.2% Carnot efficiency**. To evaluate the long life potential of the DS 1.5, one cooler has been running since October, 2013, **for a total of more than 12,460 hours** without any failure and performance degradation, another cooler has been running since January, 2015. Customers have been satisfied with its high efficiency, but there are some customers who would like more lift without increasing the size of the DS 1.5. Sunpower therefore decided to study **the feasibility of producing an increased-cooling-capacity version of the DS 1.5 with a lift as high as possible without increasing its size and without making any major design changes**. In this paper, we will explain how we determined the new design parameters. We will also explain the benefits of the high-capacity DS 1.5.



CryoTel DS 1.5 Compares Favorably to the Competition with Respect to Efficiency



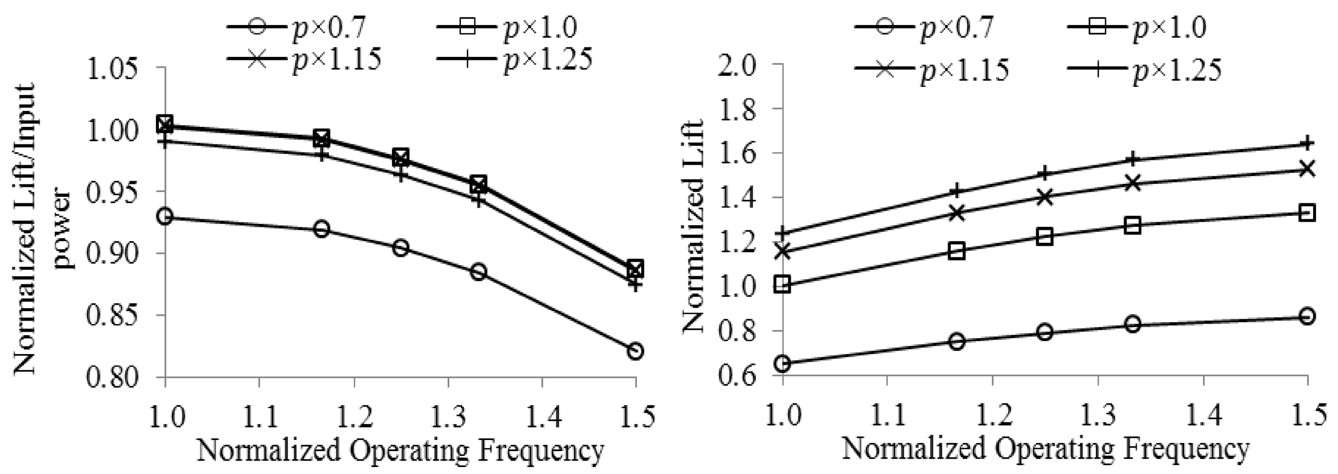
CryoTel DS 1.5 in Parallel Arrangement, & In-Line Arrangement

CryoTel® DS 1.5 Performance

Cold Tip / Rejector Temperatures	77 K / 23°C	95 K / 35°C	95 K / 70°C
Lift (watts)	1.5	2.1	1.7
Input power (watts)	30	30	30
% Carnot	14.2	15.7	14.8

Increasing the PV Work of the Wave Generator

- To meet these requirements, Sunpower has focused on **increasing the PV work of the current DS 1.5**.
- The piston cross sectional area, the piston amplitude, the pressure amplitude, and the operating frequency are factors to increase the PV work.
- We chose the **charge pressure** and **operating frequency** for this study because **they are the methods least likely to require major design changes**.
- Increasing operating frequency produces higher PV work but it increases the regenerator losses (such as the heat transfer between the regenerator material and the gas) and increases the pressure drop across the regenerator.
- Through structural and magnetic analysis, we had found the maximum point of charge pressure increase.
- The disadvantages of higher pressure are the increases of the clearance seal flow and gas bearing pumping losses, higher magnetic stress on the irons, and the reduction of the motor efficiency.
- A new **operating frequency 1.25 times that of the DS 1.5 was chosen to minimize the efficiency drop**.
- The **charge pressure was then selected to be 1.15 times that of the current pressure** because the efficiency begins to saturate around that pressure.
- These new parameters are estimated to provide about **1.4 times greater lift than that of the original DS 1.5 with about 98% of the efficiency of the original DS 1.5**.

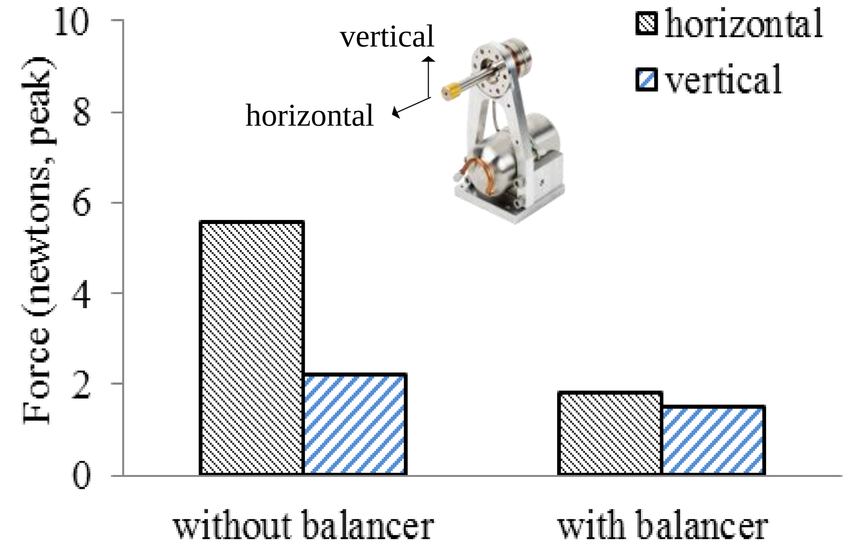


Prototype Test Results

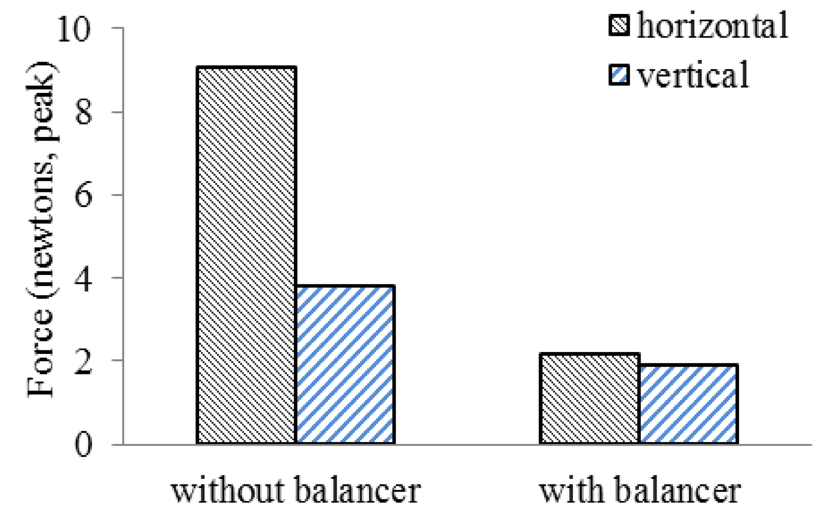
- A prototype of the high-capacity DS 1.5 design was built by modifying an original DS 1.5. The test shows **a lift of 2.1 W at 77 K with 43 W of input power, which means that it has 1.4 times greater lift than the original DS 1.5, and has 98% of the efficiency of the original DS 1.5**. These results are in line with the prediction.
- The increase in the mass of the high-capacity DS 1.5 above the mass of the original DS 1.5 is less than 0.2%. Also, **the specific mass (mass per unit of cooling power) of the original DS 1.5 is 0.8 kg/W, the specific mass of the high-capacity DS 1.5 is 0.57 kg/W, 30% better than the original DS 1.5**.
- The overall vibration levels of the original DS 1.5 and the high-capacity DS 1.5 are about the same with the passive balancers installed; **about 2 N peak is mostly from the high harmonics** because the passive balancer was designed to tune out a single frequency vibration, therefore, some of the high harmonic vibrations still exist.
- Without a passive balancer on either cooler, **the vibration on the high-capacity DS 1.5 becomes about 1.7 times greater** than the vibrations on the original DS 1.5 because the inertia force of the moving displacer increases with the square of the operating frequency.

Test Results of High-Capacity DS 1.5

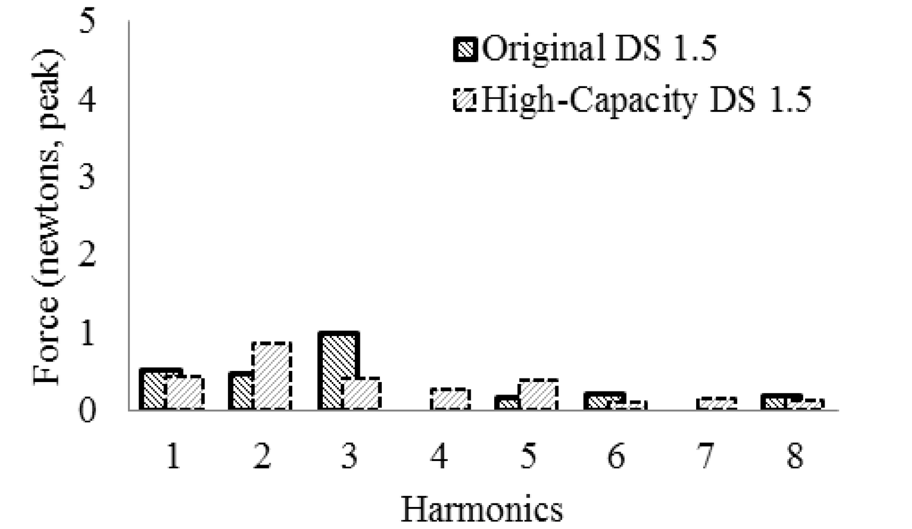
Cold Tip / Rejector Temperatures	77 K / 23°C	95 K / 35°C	95 K / 70°C
Lift (watts)	2.1	3.0	2.4
Input power (watts)	43	43	43
% Carnot	13.9	15.6	14.6



Overall Vibrations of Original DS 1.5

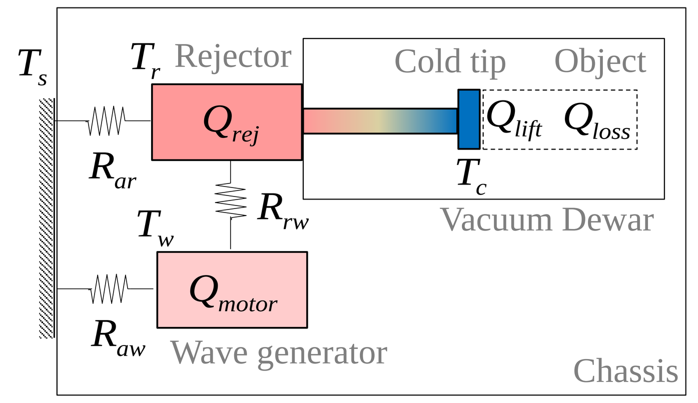


Overall Vibrations of High-Capacity DS 1.5



Harmonics of Horizontal Vibrations with Balancer

- One example of the DS 1.5 is to **cool down 80 kJ of thermal mass to 100 K which typically takes about 16 hours** at an elevated ambient temperature condition. To investigate by how much the high-capacity DS 1.5 shortens the cool-down time on that application, the cold-down times were simulated and later tested. The simulation includes the cold tip, the rejector, and wave generator thermal modeling with considering their thermal paths to the ambient temperature.



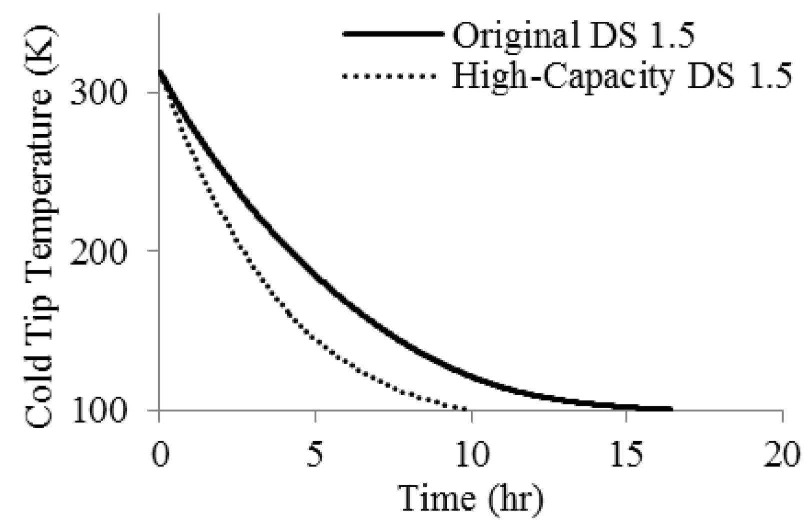
$$C_o \frac{dT_c}{dt} = Q_{net} = -Q_{lift} + Q_{loss}$$

$$C_r \frac{dT_r}{dt} = \frac{(T_s - T_r)}{R_{ar}} + \frac{(T_w - T_r)}{R_{rw}} + Q_{rej}$$

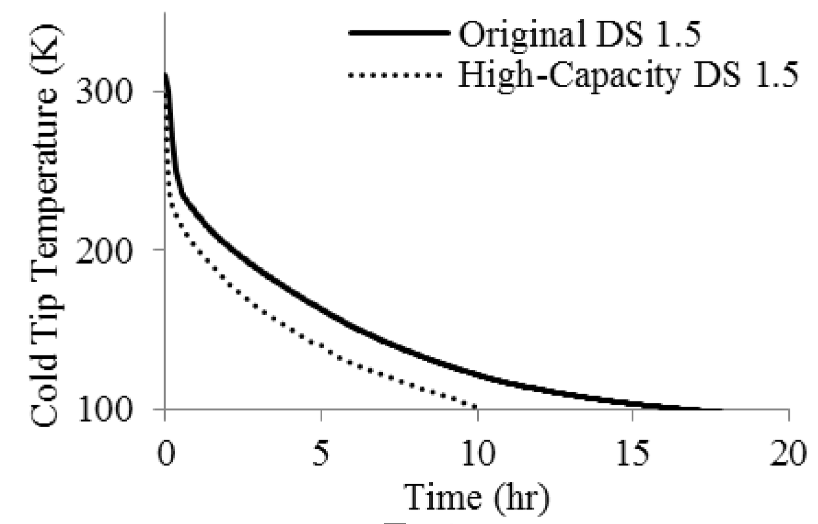
$$C_w \frac{dT_w}{dt} = \frac{(T_s - T_w)}{R_{aw}} + \frac{(T_r - T_w)}{R_{rw}} + Q_{motor}$$

Cold Tip, Rejector, and Wave Generator Thermal Modeling

In the tests, **the original DS 1.5 took 16.2 hours with 1,350 kJ of input energy, and the high-capacity DS 1.5 took 10.2 hours with 1,090 kJ of input energy**; **that's about 22% less input energy consumption, but it took 37% less time** to reach the target cold tip temperature. The predicted cool-down times and energy consumptions were close to those measured in the tests.



Simulations



Tests

CONCLUSION

- A prototype of the high-capacity DS 1.5 design was built and successfully demonstrated its feasibility to provide a lift of 2.1 W with an input power of 43 W, achieving 13.9% of Carnot without increasing its size or making any major design changes.
- Its specific mass of 0.57 kg/watt is 30% better than that of the original DS 1.5.
- The overall vibrations of the original DS 1.5 and the high-capacity DS 1.5 are both about 2 N peak with the passive balancer installed.
- Tests showed that the high-capacity DS 1.5 has a 37% faster cool-down time with 22% less input energy consumption during the cool-down time.
- We believe that the high-capacity DS 1.5 would be a preferred choice for many customers, especially those looking for higher cooling capacity and low mass.
- Sunpower plans to build more units to gain a broader range of performance data and will then decide whether to proceed with a commercial product.

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