

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

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Abstract. 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, but there are many customers who want more lift with the same size and reliability. Therefore, Sunpower performed a study on the feasibility of maximizing the lift of the DS 1.5 without increasing its size. This paper describes the analysis and test results of increasing the cooler power density by using a higher operating frequency and charge pressure. Prototype testing showed good agreement with the model. Testing performed at various frequencies and charge pressures with a few internal component changes resulted in a maximum lift of 2.1 watts with an input power of 43 watts, achieving 13.9% of Carnot. The prototype high-capacity DS 1.5 achieved 0.6 watts more lift with only a slight decrease in efficiency, and with less than 0.2% cooler mass increase. The impact on the cool-down time on a thermal mass system was tested and the cool-down time was 37% faster while consuming less input energy during that time. 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.

1. Introduction

The CryoTel[®] DS 1.5 is a split type Stirling cryocooler consisting of a 39 mm diameter cold head 128 mm in length, and a 55 mm diameter pressure wave generator 116 mm in length [1]. The wave generator includes two free pistons in a dual-opposed configuration sharing the same single compression space volume. This configuration cancels the vibration generated by the piston motion. The cold head is coupled with the wave generator through a small transfer tube so any residual vibration of the wave generator is isolated from the cold head. In this split cooler configuration, vibration on the cold head, mostly generated by the displacer movement, is small enough to use a small and light passive balancer to minimize the vibration on the cold head. An advantage of the split configuration is that the customer has several options with respect to the cold head and wave generator orientation and configuration as shown in figure 1. Our testing showed that the cooler performance does not decrease significantly until the tube reaches 150 mm in length. To give the cooler a long operating life, the DS 1.5 has gas bearings on the pistons and displacer. Gas bearings combine the use of a check valve to supply a constant pressure to the bearing pads, and sets of flow restrictors to



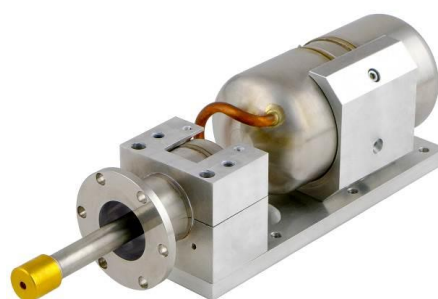
produce the bearing force. The DS 1.5 has a nominal 1.5 W lift at 77 K with 30 W of input power. Table 1 lists the cooler's performance at various temperature points.

Table 1. 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



(a)



(b)

Figure 1. CryoTel DS 1.5 in (a) parallel arrangement, & (b) in-line arrangement

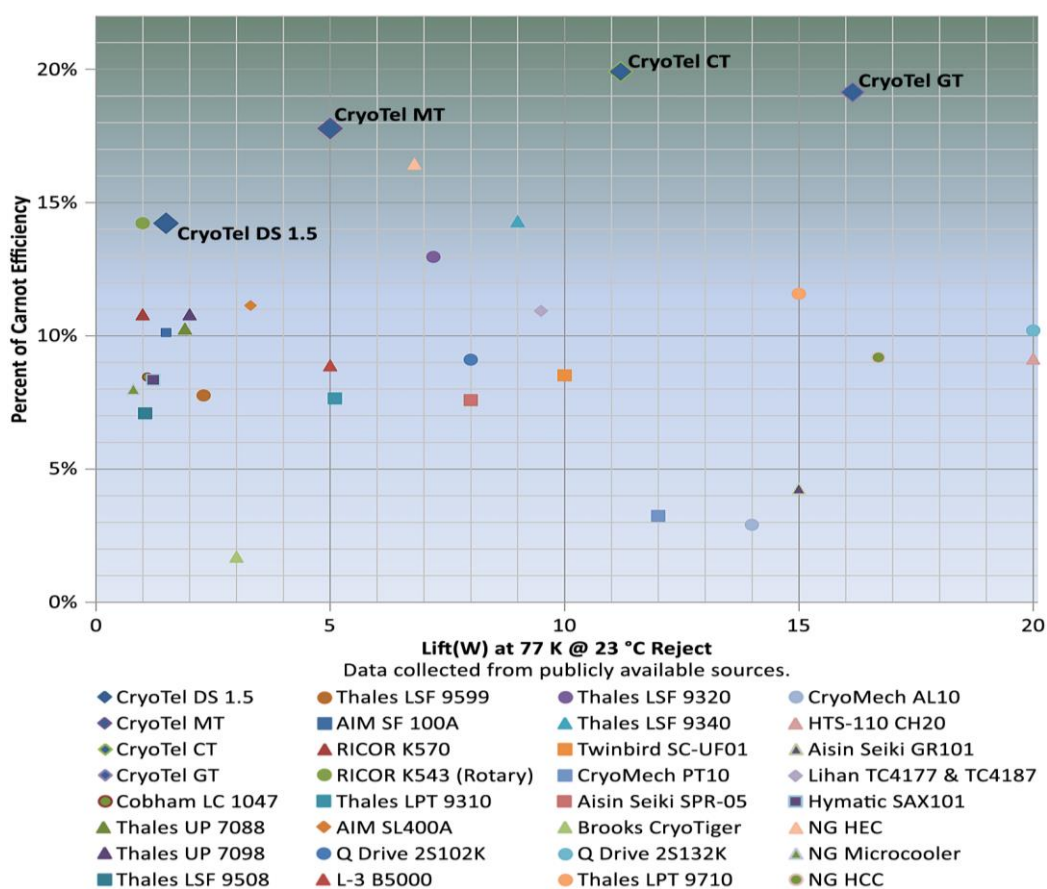


Figure 2. CryoTel DS 1.5 compares favorably to the competition with respect to efficiency

Sunpower compared commercially available cryocooler efficiencies at 77 K with 0.5 to 20 W lift ranges. Figure 2 shows the results. This data was collected from publicly available data with a rejection temperature of 23 °C. The figure shows that CryoTel cryocoolers are among the most efficient cryocoolers available.

To evaluate the long life potential of the DS 1.5, one cooler (unit 1) has been running at Sunpower continuously without maintenance since October, 2013, for a total of more than 12,460 hours. Another cooler (unit 2) has been running since January, 2015. Both units were occasionally removed from their long-term life test rig to measure their lift on a calibrated performance test rig. Figure 3 shows the results.

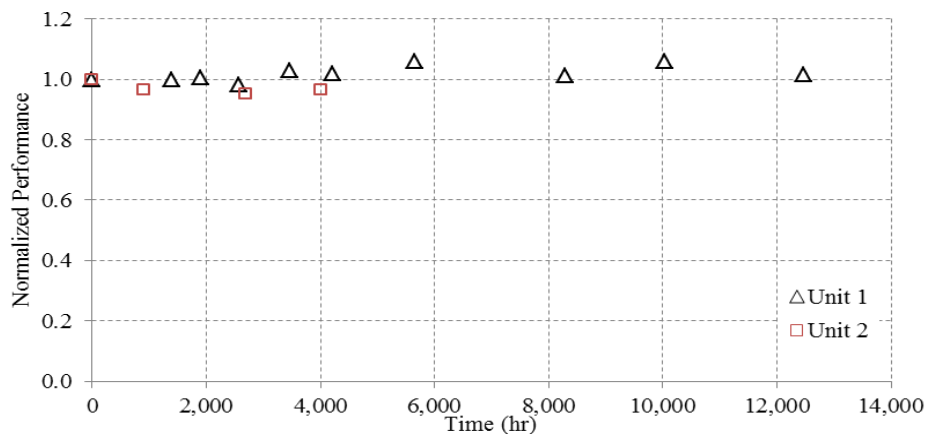


Figure 3. Long-term performance variation of the DS 1.5

Production of these units included several days of a vacuum bake-out process followed by final assembly, welding of the hermetic pressure vessel inside of a gas-filled glove box, and a number of cycles of a helium charge and purge process to remove gaseous contamination from the cryocoolers. These manufacturing processes and the non-contact gas bearing design feature helped to prevent performance degradation trends from appearing on these units.

Ever since the DS 1.5 became a Sunpower commercial cryocooler product, 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. To meet these requirements, Sunpower has focused on increasing the PV work of the current DS 1.5 by changing the operating frequency and charge pressure. In this paper, we will explain how we determined the new design parameters and how we verified them through testing. We will also explain the benefits of the high-capacity DS 1.5.

2. Increasing the PV work of the wave generator

The PV work, the power generated at the face of the pistons of the wave generator, is the cyclic integration of the instantaneous pressure wave times the volume flow rate.

$$W_{PV} = P_a A_p \pi f x_p \sin(\phi) \quad (1)$$

where, P_a is the compression space pressure amplitude, A_p is the piston cross sectional area, f is the operating frequency, x_p is the piston amplitude, and ϕ is the phase angle between pressure and piston displacement.

In PV work terms, the piston cross sectional area is a primary factor in determining power, but increasing this area would require redesign of the piston and other parts such as the cylinder, motor, and pressure vessel. Achieving higher power through increasing piston amplitude is easier; it only

requires higher voltage or adjusting the number of motor coil turns, but the piston's maximum amplitude is limited by the motor size due to magnet toggling out of the motor. The compression space pressure amplitude could be increased with a higher gas charge pressure, but higher charge pressure increases mechanical and magnetic stresses on the structure and the motor that may require some design changes to reduce stresses. Increasing operating frequency is relatively easy although it would require some adjustment of the dynamics of the moving components. After considering all the possible methods discussed above, we chose the charge pressure and operating frequency methods for this study because they are the methods least likely to require major design changes.

Increasing operating frequency produces higher PV work on the wave generator 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 [2]. The pressure drop loss through the regenerator is calculated by Sage [3] and appears to increase as the square of the frequency, and significantly degrades the performance of the cooler as shown in figure 4(a). To reduce the loss, the hydraulic diameter of the regenerator needs to be smaller, which requires smaller porosity and/or wire size. Also, even though it would increase the conduction loss, the length of the regenerator may need to be shortened to reduce the pressure drop loss, but those design changes are not considered in this study. The linear motor, however, provides a slightly positive influence on the performance of the cooler because increasing the frequency does not require an increase on the motor force. The coil loss, which is the major motor loss, remains the same even though there is a little increase in the eddy current and hysteresis losses. Because of this, the efficiency of the cooler including the motor, lift/input power, reduces the performance drop as the frequency increases as shown in figure 4(a).

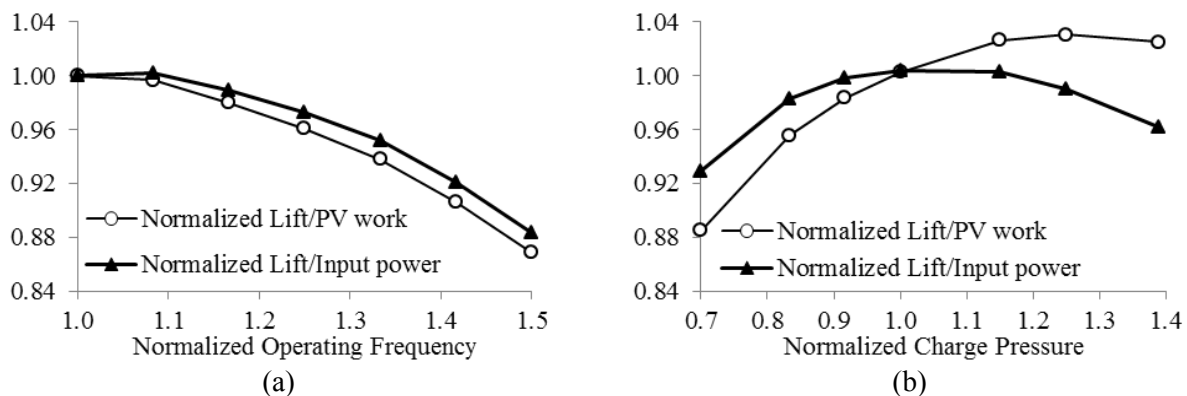


Figure 4. Efficiency versus (a) operating frequency, & (b) charge pressure

The structural analysis and testing performed on the current pressure vessel demonstrated sufficient mechanical strength margin even when using a charge pressure that is 1.5 times higher than usual. The cooler actually shows better mechanical performance (lift/PV work) with a little higher charge pressure as shown in figure 4(b). Another benefit of higher pressure is on the gas bearing capacity. Since the levitation force of the gas bearing is proportional to the pressure amplitude, this higher pressure levitates the moving components better and helps to extend the life time of the cooler. 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. The clearance seal flow and the gas bearing modeling showed the leakage flow and the bearing pumping powers would be about one watt more which would not be a big impact considering input power gain. A magnetic finite element analysis showed that the magnetic saturation on the irons begins to occur at 1.3 times the charge pressure; therefore, the pressure should be less than this. The reduction of the motor efficiency is because the motor needs to provide more force as the pressure goes up, and then the coil and the iron losses on the motor increase as the square of the pressure increase, decreasing the overall efficiency of the cooler as shown in the figure 4(b).

The operating frequency and the charge pressure effects are combined and shown in figure 5. As discussed previously, the efficiency decreases as the frequency goes up, therefore, a new operating frequency 1.25 times that of the DS 1.5 was chosen to minimize the efficiency drop. The charge pressure, p in the figure, was then selected to be 1.15 times that of the current pressure because the efficiency begins to saturate around that pressure and because that pressure still has enough room to prevent the motor irons from being saturated. 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.

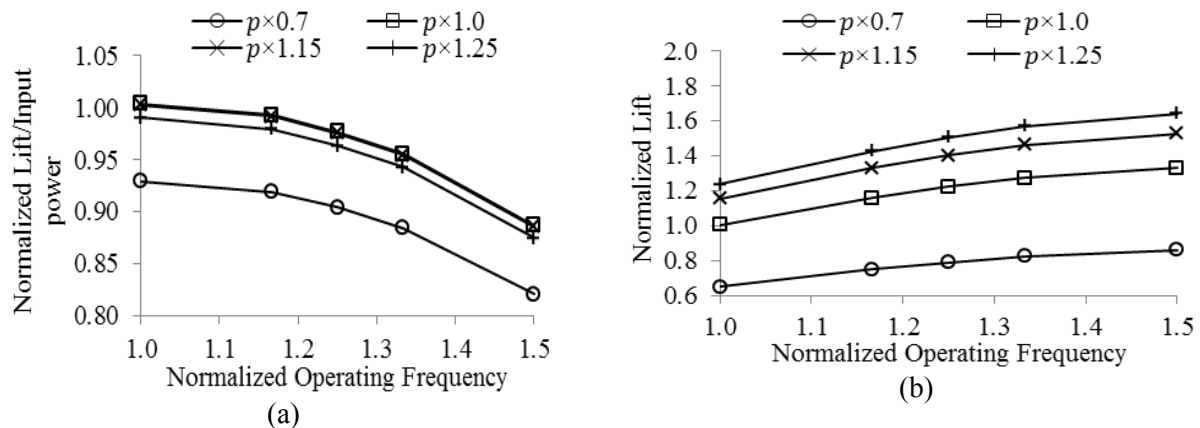


Figure 5. Combined operating frequency & charge pressure effects on (a) efficiency, & (b) lift

3. Prototype test results

A prototype of the high-capacity DS 1.5 design was built by modifying an original DS 1.5. It was then tested on a calibrated performance test rig. The test result, provided in Table 2, show 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.

Table 2. Test results of the high-capacity DS 1.5 prototype

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

Ray Radebaugh's survey showed that 10% to 15% of Carnot at 80 K is typical of some of the best commercial cryocoolers [4], which means that both the original DS 1.5 and the high-capacity DS 1.5 can be considered high-efficiency cryocoolers in the commercial market. 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 (which is already competitive), but the specific mass of the high-capacity DS 1.5 is 0.57 kg/W, 30% better than the original DS 1.5. Therefore, 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.

Since the high-capacity DS 1.5 operates off of 13 W more input power than the original DS 1.5, the vibration from the operation of the cooler may increase. The wave generator of the DS 1.5 is a dual-opposed configuration, therefore the vibration generated by the two moving pistons cancel each other out regardless of the input power. But the vibration on the cold head could be greater on the high-capacity DS 1.5 because the inertia force of the moving displacer increases with the square of the operating frequency. However, an optional passive balancer can be installed on the end of the DS 1.5's

cold head pressure vessel to tune out the vibration on the cold head; therefore, the high-capacity DS 1.5 should have basically the same amount of vibration as that of the original DS 1.5. An original DS 1.5 and the prototype high-capacity DS 1.5 ran with and without their passive balancers while we measured vibration levels. To isolate the mounting effects on the cooler vibration to the ground, the coolers were suspended from a rigid rod with flexible rubber wires.

Figure 6 shows the horizontal and vertical vibration measurements. 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 peaks 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 as shown in figure 7. 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 (as discussed previously).

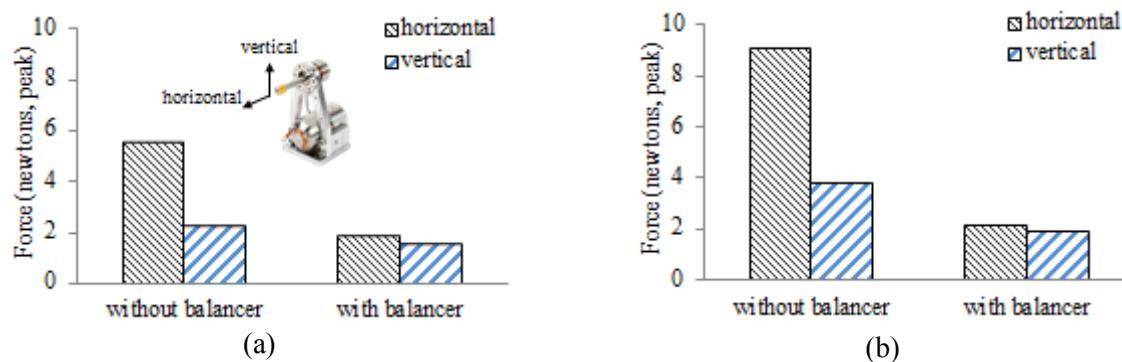


Figure 6. Overall vibration levels of the (a) original DS 1.5, & (b) high-capacity DS 1.5

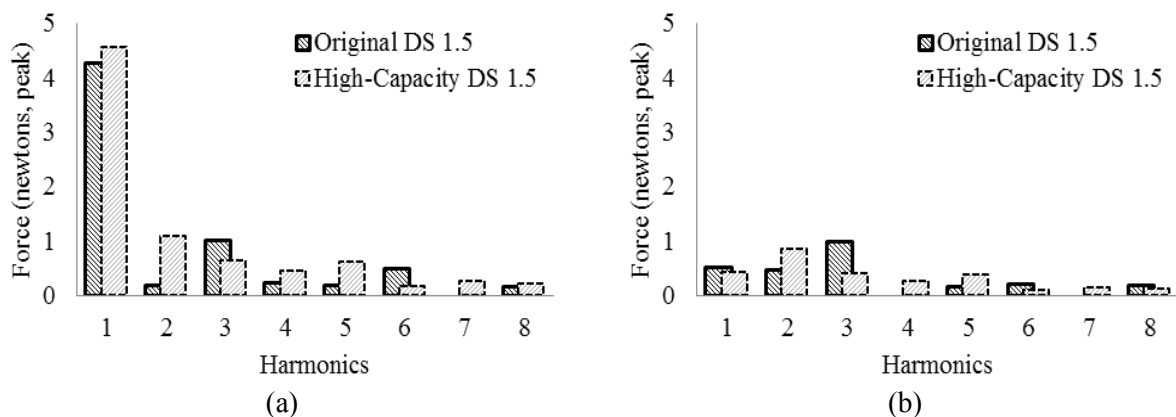


Figure 7. Harmonic components of horizontal vibrations (a) without passive balancer, & (b) with passive balancer

4. Cool-down time

Another advantage of the high-capacity DS 1.5 is that it provides a much faster cool-down time because of its higher lift. One application 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. To simplify the calculation procedure, the specific heats and thermal conductivities of the materials were assumed to be an average value from their operating temperature range. From the energy balance for the cold tip of the cryocooler we have

$$C_o \frac{dT_c}{dt} = Q_{net} = -Q_{lift} + Q_{loss} \quad (2)$$

where, C_o is the heat capacitance of the object being cooled, T_c is the cold tip temperature, t is the time, Q_{net} is the net heat on the cold tip, Q_{lift} is the lift at the cold tip, and Q_{loss} is the net loss such as the generated heat from the object, the conduction heat through wires, and the radiation heat from ambient.

The heat lift depends on the cold tip and the rejector temperatures, therefore, as measured lifts with the function of the cold tip temperature at a rejector temperature point are used but a lift degradation factor, A in the figure 8, is considered to account the rejector temperature effects on the lift. For the net loss, empirical data tested at various cold tip and ambient temperature points are used in the simulation. The thermal paths of the rejector and the wave generator and the input power determine the rejector and wave generator temperatures which affect the lift at the cold tip, the thermal modeling of the rejector and wave generator takes these variables into account, but they are only expressed by the conduction heat transfer as shown in figure 8 because the convective heat transfer inside of the chassis is minor in this application.

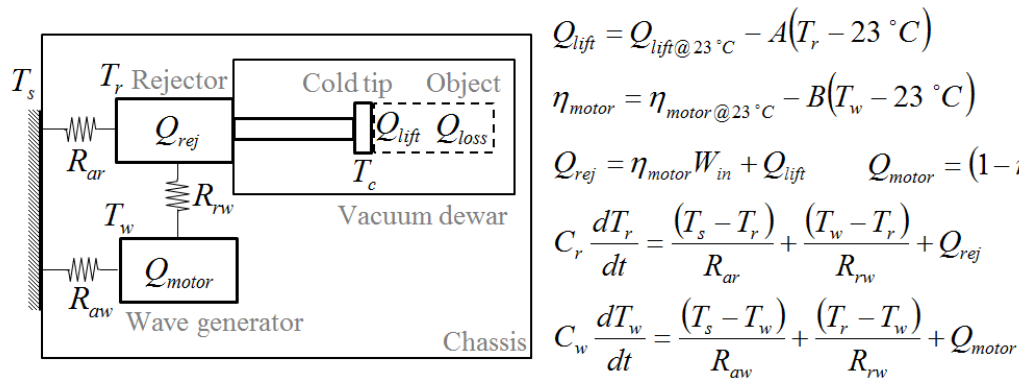


Figure 8. Rejector & wave generator thermal modeling

$$\frac{d}{dt} \begin{bmatrix} T_r \\ T_w \end{bmatrix} = \begin{bmatrix} -\left(\frac{1}{C_r R_{ar}} + \frac{1}{C_r R_{rw}} \right) & \frac{1}{C_r R_{rw}} \\ \frac{1}{C_w R_{rw}} & -\left(\frac{1}{C_w R_{rw}} + \frac{1}{C_w R_{aw}} \right) \end{bmatrix} \begin{bmatrix} T_r \\ T_w \end{bmatrix} + \begin{bmatrix} \frac{Q_{rej}}{C_r} + \frac{T_s}{C_r R_{ar}} \\ \frac{Q_{motor}}{C_w} + \frac{T_s}{C_w R_{aw}} \end{bmatrix} \quad (3)$$

where, T_s is the temperature of the chassis, T_r is the temperature of the rejector, T_w is the temperature of the wave generator, C_r is the heat capacitance of the rejector, C_w is the heat capacitance of the wave generator, R_{aw} is the thermal resistance between the wave generator and the chassis, R_{ar} is the thermal resistance between the rejector and the chassis, R_{rw} is the thermal resistance between the wave generator and rejector, Q_{rej} is the heat rejection on the rejector, Q_{motor} is the heat generation on the motor, η_{motor} is the motor efficiency, A is the lift coefficient with respect to the rejector temperature, and B is the motor efficiency coefficient with respect to the wave generator temperature.

By solving the energy balance equations for the cold tip, the rejector, and the wave generator, the predicted cold tip temperatures were plotted in figure 9(a). The simulation predicted that the original DS 1.5 would take 16.4 hours with 1,200 kJ of input energy consumption during the cool-down time, but the simulation predicted that the high-capacity DS 1.5 would take 9.9 hours with 1,053 kJ of input

energy consumption. Tests were also performed and the results plotted in figure 9(b). 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. It appeared that there were some differences in the cold tip temperature drop trends (from the ambient to around 200 K) between the simulation and the tests. These differences may be due to the inaccuracy of the properties or the modeling, but the predicted cool-down times and energy consumptions were close to those measured in the tests.

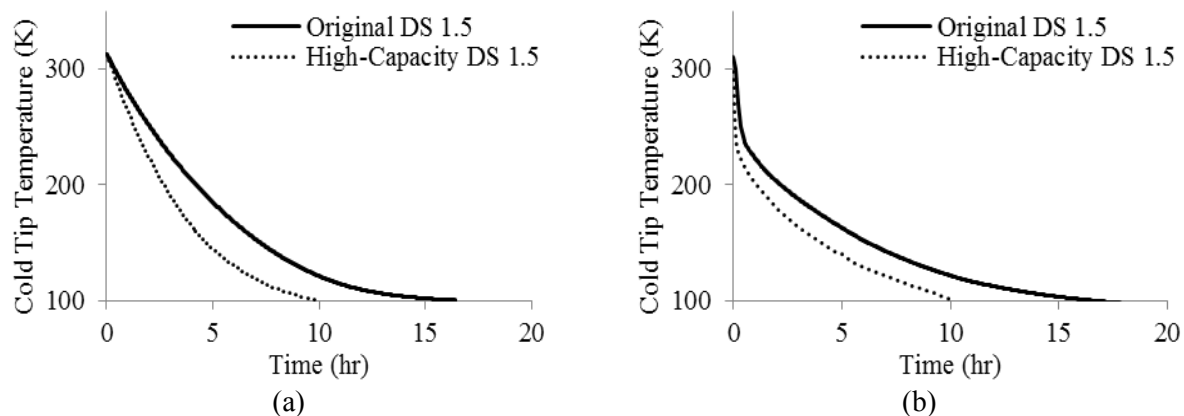


Figure 9. Cool-down times with (a) simulations, & (b) tests

5. Conclusion

A high-capacity version of the DS 1.5 was built by modifying an original DS 1.5. We then 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. It achieved 0.6 W more lift with only a slight decrease in efficiency. Its specific mass of 0.57 kg/watt is 30% better than that of the original DS 1.5. Therefore, 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. 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. Since this prototype high-capacity DS 1.5 showed good results, 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.

6. Acknowledgements

The authors wish to thank Bethany Hatch, Brendan Burns, Brian Johnson, Jesse Johnson, Kevin Flaim, Mike McCarty, and Ron Ives at Sunpower, Inc. for their support of this work.

7. References

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