Coated Regenerator for 30K Stirling Cryocoolers

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ABSTRACT

Many next-generation spaceborne electro-optical devices and emerging terrestrial superconducting devices need to be operated near 30 K and thus require efficient cooling in this temperature range. The thermal efficiency of current single-stage regenerative cryocoolers is largely hampered by the limited heat capacity of regenerators at this low temperature range. To overcome this limitation, Creare has developed a reliable process to deposit a layer of high heat capacity material on a regenerator matrix. The coating process has features to enhance the adhesion of the coating on the substrate and uniformity on the matrix elements. This paper first presents measured heat capacity and pressure drop of coated regenerators, and compares them with results for an uncoated regenerator. Next, the paper presents the enhanced performance of Sunpower Inc. cryocoolers that have incorporated the coated regenerator elements.

INTRODUCTION

Many of NASA's planetary missions require small, long-life, low-cost, low-vibration coolers to provide reliable cooling for detectors and sensors. In these missions, power is more difficult to generate due to a much lower solar flux. Consequently, reducing the cryocooling systems' power is even more critical than for earth-orbiting satellites. Reducing mass is also extremely important in missions that involve landing on another planet. The development of current cryocooler technology for space, however, has been driven almost exclusively by satellites in low earth and geosynchronous orbits where spacecraft heat rejection temperatures are typically between 300 K to 320 K. These cryocoolers are not able to efficiently take advantage of the cryogenic heat sinks available during planetary missions to reduce cooler size, mass, and power input. Furthermore, next-generation electro-optical devices, such as superconducting MgB2 thin-film bolometers, whose critical temperature is about 38 K [1], require efficient coolers that can maintain their operating temperature below 35 K. Current miniature regenerative cryocoolers cannot provide efficient cooling at this temperature range due to the poor thermal efficiency of their regenerators. For these reasons, under a NASA SBIR program, Creare and Sunpower developed and demonstrated a low-temperature Stirling cryocooler that employs an advanced regenerator to efficiently provide cooling at 30 K while rejecting heat at 150 K. The cooler uses a modified version of Sunpower's commercially available compressor and displacer and an advanced coated regenerator to provide high performance with low development costs.

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SHORTCOMINGS OF CURRENT SMALL, LOW-TEMPERATURE REGENERATIVE CRYOCOOLERS

Most low-cost, small-scale cryocoolers for tactical and low-cost space applications are regenerative cryocoolers. These coolers can achieve as high as 20% of Carnot COP when providing cooling at near 80 K and rejecting heat at 300 K. However, the efficiency of these small coolers drops off very rapidly as the cooling temperature decreases, and there is typically no net cooling at temperatures below 40 K. There are no existing single-stage Stirling cryocoolers that can operate efficiently to provide cooling at 30 K and reject heat at 150 K. The poor performance is mainly caused by the performance degradation in the regenerator at lower temperature. Secondary performance parameters such as internal seal leakage, running clearance in piston and displacer, and dynamics of displacer are important, but can be addressed by minor design changes.

Regenerator Thermal Performance is Critical to Cooler Efficiency

The performance degradation at low temperature is mainly caused by the poor performance of the regenerator, which directly affects the gas temperature entering the expansion space. The temperature difference between the gas entering the expansion space and the cooler's cold end must be very small. This temperature difference represents a heat leak to the cold end that will proportionally reduce the net cooling power for the cryocooler. Minimizing this temperature difference is the key to achieving high efficiencies and low cooling temperatures for Stirling cryocoolers, as well as for other types of regenerative cryocoolers. This can be achieved by enhancing the heat transfer between the gas flow and the regenerator matrix to reduce the temperature difference between the gas and the matrix, and by using matrix material with high volumetric heat capacity to reduce its cyclical temperature change. Finding appropriate matrix materials that have high volumetric heat capacity at low temperature and are suitable for regenerator fabrication, however, is very challenging.

Regenerators have Low Heat Capacity at Low Temperature

At low temperature, the specific heat (c_p) of regenerator matrix materials falls off sharply with decreasing temperatures (T) below about 40 K (Fig. 1), proportional to the cube of the temperature ($c_p \propto T^3$) according to Debye theory. The decrease in specific heat substantially reduces the thermal mass of the regenerator at the cold end, limiting its capacity to cool the gas flowing to the cold expansion space. The low thermal capacity in the regenerator causes a large temperature swing

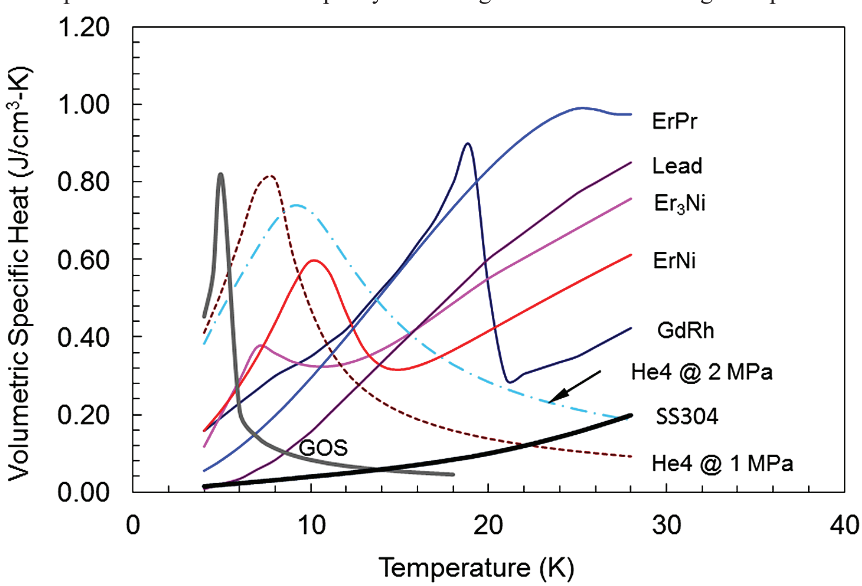

Figure 1 Volumetric heat capacity of some candidate materials at low temperature.

during periodic heat transfer and significantly reduces the efficiency of the regenerator. The regenerator ineffectiveness is a strong function of the heat capacity ratio of the regenerator matrix to the helium shuttle mass. For the same heat transfer performance, reducing the heat capacity ratio can increase the ineffectiveness several-fold [2]. Reducing the thermal effectiveness in the regenerator substantially reduces the cryocooler's net cooling power and limits its ability to reach very low temperatures.

The problem of low thermal capacity in low-temperature regenerators cannot be solved by simply increasing the regenerator size. Increasing the size of a regenerator will increase its heat transfer area and heat capacity. However, these benefits are offset by the penalties of a larger heat load in a regenerator due to a larger regenerator void volume. A larger void volume increases compression heating and expansion cooling associated with the pressure oscillation in the regenerator, and also increases the gas flow rate at the warm end of the regenerator because of a larger dead volume, requiring a larger compressor.

Fabricating Regenerator from Materials with High Heat Capacity at Low Temperature

Current research efforts on enhancing low-temperature regenerator performance focus on developing methods to fabricate the regenerator matrix out of compounds that have relatively large volumetric heat capacities at low temperatures in the vicinity of their magnetic ordering transition temperatures (Fig. 1). However, it is very difficult to use these compounds to produce small uniform spheres for packed beds or mesh screen with thin wires for a plate stack [3]. For these reasons, a practical approach is needed to fabricate a regenerator with high heat capacity compounds with uniform dimensions to promote uniform flow distribution in the regenerator and enhance the effective heat capacity of the regenerator.

OVERALL TECHNICAL APPROACH FOR EFFICIENT A 30 K STIRLING COOLER

Our approach for a 30 K cooler with a 150 K heat sink is a modified version of a Sunpower CryoTel® Model DS 1.5 cryocooler enhanced with a proprietary high heat capacity coated regenerator, as shown in Fig. 2. Sunpower's miniature Stirling coolers are among the most efficient coolers commercially available. The Model DS 1.5 cryocooler uses a dual-opposed-piston pressure wave generator and a separate cold head to minimize exported vibration at the cooling surface. The cooler employs a gas bearing technology to prevent piston contact and thus enhance the cooler reliability. When rejecting heat at about 300 K,

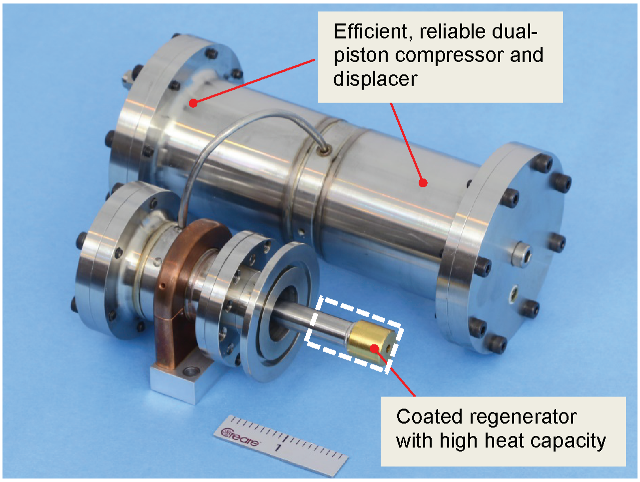

Figure 2. Highly efficient, low-cost, reliable cryocooler with coated regenerator. The advanced regenerator enables a modified Sunpower DS 1.5 cooler to provide 0.20 W cooling at 30 K with a 150 K heat sink and an input power of 12 W. The cooler is built on technologies that can achieve Mean Time to Failure of 120,000 hr. The current prototype cooler mass is about 2.00 kg and can be reduced to below 1.2 kg for a flight cooler. The current brassboard compressor has an overall diameter and length of 55 mm and 160 mm, respectively, and can be reduced to 55 mm and 119 mm for a flight cooler.

based on public literature, the thermal efficiency it achieves is the highest among the coolers with cooling capacity in the range of 0.5 to 2.5 W. This cooler is built on technologies that can achieve a Mean Time to Failure of 120,000 hr.

COATED REGENERATOR FABRICATION

To overcome the challenges in existing approaches to fabricate regenerators with high heat capacity compounds, Creare's approach is to develop a sputtering deposition process to apply coatings to a three-dimensional porous regenerator scaffold made of, for example, stacked stainless steel (SS) screen or random SS fibers, to increase their effective heat capacity and thus improve regenerator performance.

Sputtering is a simple, low-cost baseline approach that allows very good alloy composition control. The advantages of sputtering (and several other PVD coating approaches) over non-PVD coating approaches include the ability to deposit high purity alloys to tune the alloy composition, and the ability to tune the coating mechanical properties. Electroplating, on the other hand, cannot typically deposit alloys, offers little control of the coating area, requires compatibility with hazardous chemical baths, and generates liquid hazardous waste. Coating by dip-coating in molten alloy or thermal spraying is unsuitable because these techniques would plug the fine screen holes.

We developed a proprietary custom sputtering facility and coating deposition process to produce high quality coated regenerator scaffolds. The average coating thickness can be controlled by the sputtering gun input powers and the total coating time. The resulting alloy coating on the fibers of the sintered disks is robust, and distribution of the coating on the fibers is sufficiently uniform, as shown in the Fig. 3. Separate effects testing shows that the adhesion of the coating to substrate is strong enough that cutting disks using an Arch punch from a sheet of coated substrate material does not result in significant damage to the coating or production of loose particles. Repeated thermal cycling of the coated regenerator material from room temperature to normal liquid nitrogen temperature shows no sign of coating delamination.

TESTING OF COATED REGENERATOR SPECIFIC HEAT AND PRESSURE DROP

Test Setup

Shown in Fig. 4 is the cryogenic test setup used to measure the thermal wave breakthrough time across the regenerator. Helium from a research-grade gas cylinder is first passed through a mass flow meter and then through a gas cleaning subsystem (not shown) to remove contaminants. Next, it passed through a cold plate attached to a GM cold head to cool down to about 30 K. Finally, it is passed through a heater and then enters the regenerator. At the beginning of each test, the heater was disabled and the entire regenerator was cooled down to a temperature very close to the temperature setpoint of the GM cold head. Once the regenerator temperature reached a steady state, the thin-film heater was turned on to rapidly raise the temperature of the helium flow entering the regenerator by 2 K to 3 K. After the thermal wave passed through the regenerator, the heater was turned off,

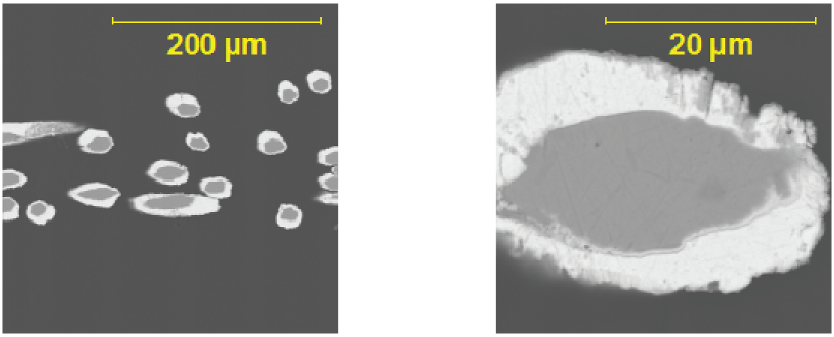

Figure 3. Scanning electronic scope images of cross-sectioned coated regenerator scaffold. The scaffold appears medium gray and the coating appears light gray.

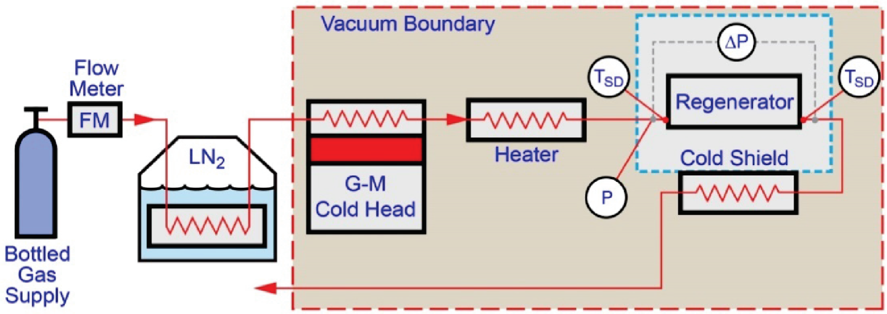

Figure 4. Test setup to characterize subscale regenerator heat capacity and thermal performance.

introducing another thermal wave through the regenerator, which cooled the regenerator by 2 K to 3 K back down to the cold head temperature.

To reduce parasitic heating into the regenerator, we placed a cooling shroud (a tightly spaced copper coil) around the regenerator. The cooling shroud was cooled by the exhaust flow from the regenerator. A relatively high-speed data sampling rate of 100 Hz was used to measure and record the transient gas flow temperatures at the inlet and outlet of the regenerator.

Measured Heat Capacity

Shown in Fig. 5 are the inlet and outlet flow temperature profiles in a typical transient thermal test. The thermal breakthrough time was calculated for each test, and a simple algorithm was used to determine the temperature lift-off point of each curve to enhance the consistency of the breakthrough time measurement. Shown in Fig. 6 is a summary of the measured heat capacity values of the regenerator materials. The measured values are close to the predicted values at temperatures higher than 40 K, but are slightly lower than predicted values as the temperature decreases below 40 K. The heat capacity of the coated regenerator matrix is about 2.4 times that of the uncoated scaffold. Based on the measured values and the target regenerator operating conditions, the heat capacity of the coated regenerator matrix is about 4.0 times that of the helium shuttle mass at 40 K and about 2.5 times at 30 K.

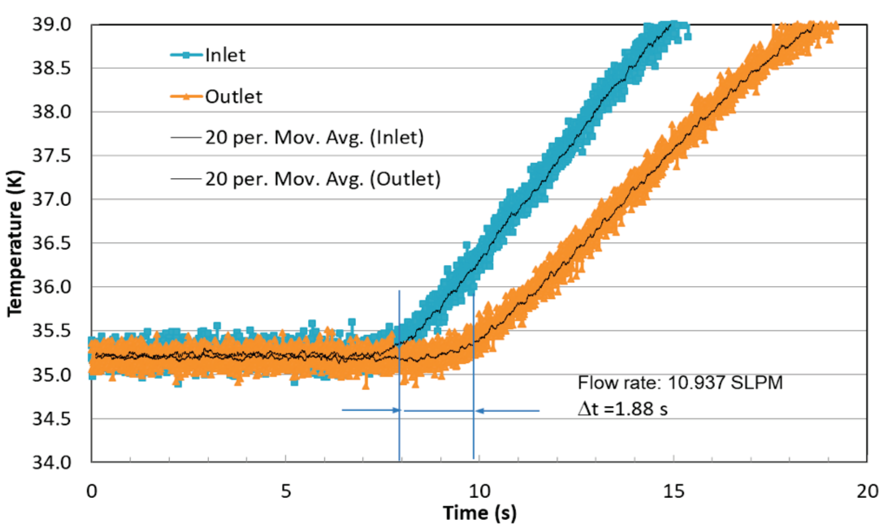

Figure 5. Typical sample inlet and outlet temperature during thermal wave breakthrough testing.

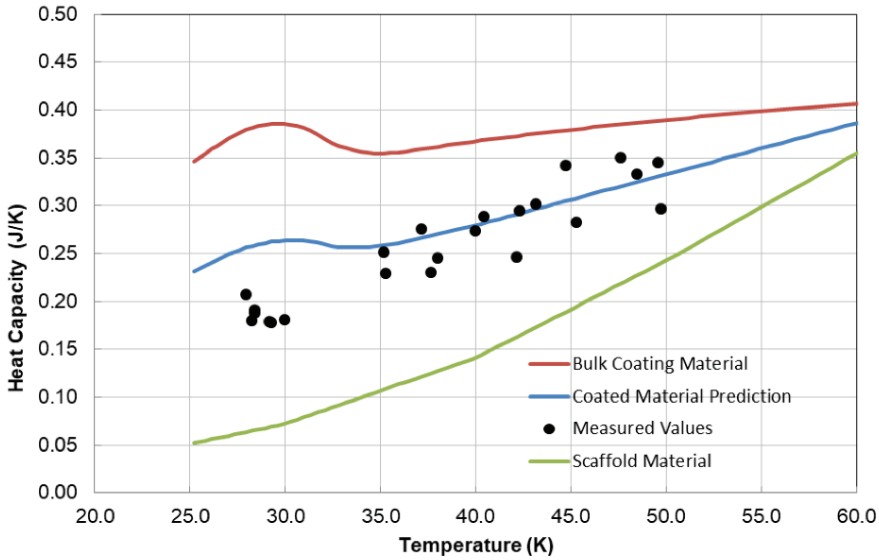

Figure 6. Comparison of measured heat capacity of coated samples to predicted values based on the mass of the scaffold and coating materials. The measured values are slightly lower than the predicted values at temperatures below 30 K. The "Bulk Coating Material" curve assumes the disks are entirely made of coating material with the same volume.

Measured Pressure Drop

Shown in Fig. 7 are comparisons of the pressure drops across the coated sample with those across the uncoated samples. The pressure drop across the coated sample is 1.84 times that of the uncoated disks. The higher pressure drops across the coated disks were expected due to the reduced flow area. Shown in Fig. 8 are the measured pressure drops that are consistent but slightly lower than predicted values from the model [4]. The good agreement confirms the reliability of the measurement, as well as the uniformity of the coating on the disks.

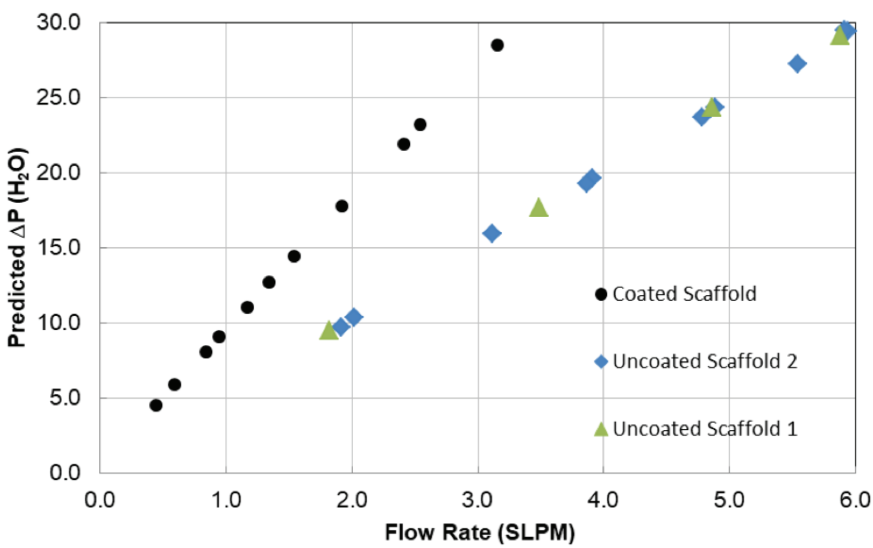

Figure 7. Comparison of pressure drop across test samples. At the same mass flow rate, the pressure drop across the coated sample is about 1.84 times that across the uncoated sample.

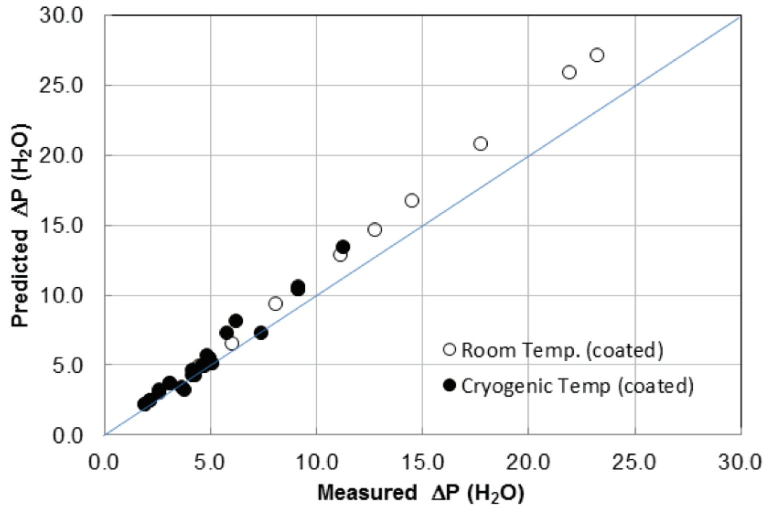

Figure 8. Comparison of measured pressure drop with predicted values for sample #1 with coated disks. The measured value is slightly lower than predicted values from the model [4].

Performance of Cryocooler with Coated Regenerator

For the intended application, the DS 1.5 cooler heat sink temperature will be 150 K, significantly lower than typical terrestrial cryocooler heat rejection temperature. This environmental condition has effects on the charge pressure, the displacer spring, critical running clearances of the piston and displacer, and the characteristics of internal seals. Sunpower successfully revised the design and fabrication of the DS 1.5 cooler accordingly to enable the pressure wave generator and the warm end of the cold head to reliably operate at 150 K. Sunpower then incorporated the coated regenerator material into the cold end of the regenerator and conducted iterative design and testing to optimize the regenerator configuration to mitigate the impact of the higher flow resistance at the coated section of the regenerator.

Test results at Sunpower and Creare show that at an input power of 15 W and a sink temperature of 150 K, the cooler reached a no-load temperature of 21.7 K, as shown in Fig. 9. The cooling power

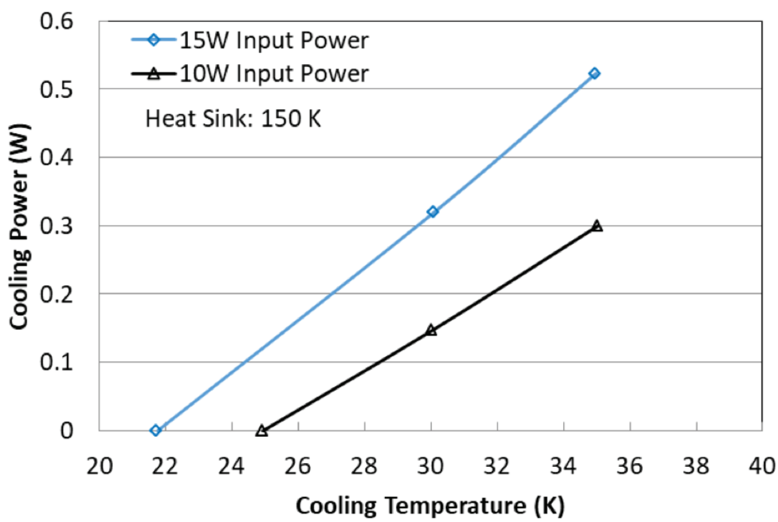

Figure 9. Coated regenerator performance results at 15 W (top) and 10 W (bottom) input power.

Table 1. Performance Improvement With Coated Regenerator Disks in Sunpower GT and MT Coolers.

GT Cooler with 240W input power and 23°C heat sink				MT with 80W input power and 23°C heat sink			
Standard		Coated		Standard		Coated	
Tcold (K)	Lift (W)	Tcold (K)	Lift (W)	Tcold (K)	Lift (W)	Tcold (K)	Lift(W)
77	16.8	77	17.1	80	5.7	80	6.2
35.9	0	27.2	0	40.5	0	33.7	0

at 30 K was 320 mW, corresponding to a Carnot efficiency of 8.5%. At 10 W of input power, the no-load temperature was 24.9 K and the cooling power at 30 K was 150 mW, corresponding to a Carnot efficiency of 6.0%. The efficiency of the cooler is reasonably higher at such low input power levels and low cooling temperatures. Sunpower also incorporated the coated regenerator material into their GT and MT coolers to improve their performance at low temperatures. The coated regenerator material reduces their no-load cooling temperature by 8.7 K and 6.8 K, respectively (Table 1), enabling them to reach a cooling temperature below 35 K. The coated regenerator material also slightly enhances their cooling power at 77 K.

DISCUSSION

An advanced coating process was developed to apply a high heat capacity coating to three dimensional porous regenerator scaffold material to enhance the regenerator heat capacity at cryogenic temperatures. The effective thermal mass and flow resistance of the coated regenerator matrix are consistent with predicted values. The coated regenerator material increases the heat capacity of the regenerator cold end section by a factor of about 2.5. The coated regenerator material enables a small modified commercial cooler to efficiently absorb heat at 30 K and to reject it at 150 K, reaching a Carnot efficiency of 8.5% at an input power of 15 W.

ACKNOWLEDGMENT

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