

ENHANCED PERFORMANCE OF THE BEI 0.5 WATT MINI-LINEAR STIRLING COOLER

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ABSTRACT

The BEI B500C Mini-Linear Cooler delivers 0.5 Watt of refrigeration at 80 K with an input power of less than 21W (at 23C case temperature). To meet more stringent requirements, the design of this cooler has been modified to enhance its performance. The new refrigerator, known as the B512C Mini-Linear Cooler has a more efficient motor with less dead volume and parasitic heat loads down the coldfinger. It can provide ~0.6 Watt of cooling at 80K. The cooldown time from room temperature to 73K is less than 8 minutes with 250 joules of thermal mass and a case temperature of 60C. At the same demanding case temperature of 60C, the refrigeration capacity is >0.25 Watt (with a cap of 11 Volt or 22 Watt), and the cooler can deliver 0.15 Watt of cooling with less than 13 Watt of input power. In this paper, the enhanced performance of this cooler is discussed in detail together with some of the analyses which lead to the final product.

INTRODUCTION

The progressively more demanding requirements on the 0.5 Watt Linear Cooler have prompted BEI to modify the design of the mini-linear cooler. The enhanced performance of this new design is presented in this paper.

Table 1- Summary on the Enhancement of Cooler Performance

	Old Baseline	Improved Regenerator Efficiency	Improved Motor Efficiency	Reduced Parasitic Heat Loss
Cooldown Time to 73K	3:56	S1- 4:14 S2-4:47 S3-4:35 (Avg. 4:45) S4-4:39 S5-5:06	C1751- 4:26 C1752- 4:33 C1753- 4:47 (Avg. 4:35)	C1751- 4:10 C1752- 4:34 C1753- 4:17 (Avg. 4:20)
Input Power @ 73K 150 mW Ambient: 60 C	14.6 W	S1- 14.7 W S2- 14.1 W S3- 13.7 W(Avg. 14W) S4- 13.3 W S5- 14.2 W	C1751- 10.2 W C1752- 10.3 W C1753- 12.5 W (Avg. 11W)	C1751- 9.5 W C1752- 10.6 W C1753- 11.37 W (Avg.10.5W)
Input Power @ 73K 150 mW Ambient: 23 C	10.7 W	S1- 9.8 W S2- 10 W S3- 10.4 W(Avg. 10.4W) S4- 10.4 w S5- 11.4 W	C1751- 7.97 W C1752- 7.55 W C1753- 8.9 W (Avg.8.1W)	C1751- 6.85 W C1752- 6.7 W C1753- 7.83 W (Avg. 7.1W)
Input Power @ 78K 150 mW Ambient: 23 C	9.1 W	S1- 8.7 W S2- 8.4 W S3- 8.8 W (Avg. 8.92 W)	C1751- 6.99 W C1752- 6.67 W C1753- 8.25 W (Avg.7.3W)	C1751- 6.25 W C1752- 5.9 W C1753- 6.76 W (Avg. 6.3W)

THE OLD DESIGN OF THE BEI B500C COOLER

The typical performance of the old baseline BEI B500C cooler is listed in the second column of Table 1. In order to enhance the performance of the B500C coolers to meet the stringent requirements of some of our customers, BEI has investigated ways to improve the following areas of the cooler, namely, the effectiveness of the regenerator, efficiency of the motor, and parasitic heat loss.

REGENERATOR EFFECTIVENESS

The regenerator is one of the most critical components of the cryocooler. It absorbs the heat energy from the working gas as it passes from the hot end of the displacer to the cold end and releases the energy to the gas stream as the flow reverses in direction. By improving the effectiveness of the regenerator, one can enhance the performance of the cooler by cutting down the enthalpy flow, which decreases the PV work of the thermodynamic cycle. There are three major considerations in the design of a regenerator.

Regenerator configuration

The conventional method of using screens as the regenerator material is only one of the many possible configurations, including parallel plates and bundled tubes. The effectiveness of a regenerator configuration is generally characterized by the amount of heat transfer divided by the pressure drop across the regenerator. Recently, etched-foil regenerators, based on the parallel plate concept, stirred up quite a bit of interest in the cryocooler field. Some believe that by

keeping the transport within the regenerator in the developing flow regime, one can maximize the heat transfer and minimize the pressure drop. Etched-foil regenerators were built and tested at BEI. It was concluded that one should be cautious in applying the etched-foil technique to pneumatically driven split Stirling coolers, for the extremely low pressure drop in the regenerator may change the optimum phase angle between the displacer and piston motion, and lead to adverse effects.

Regenerator dimensions-

It is quite obvious that each cooler has an optimum dimension of the regenerator for the best performance. Bigger and longer regenerators result in good heat transfer with the working gas and reduced axial heat conduction, but the presence of extra dead volume degrades the performance. On the other hand, too small a regenerator might have limited dead volume, but the adverse heat transfer effects are not favorable. Figure 1 shows the input power as a function of regenerator length as predicted by a Hybrid Computer Model (reference 1 to 8), showing the optimum length for the lowest input power.

Regenerator material-

The choice of material is crucial for the success of a regenerator. The material used should have a high heat capacity for heat transfer and low thermal conductivity to minimize parasitic heat loss. Common material used nowadays are stainless steel and phosphor bronze. Etched foil regenerators made of nickel were also fabricated at BEI.

Five prototype expanders (S1, S2, S3, S4 and S5) with improved screen-regenerators were built and tested, and the results are summarized in the third column of Table 1. The new regenerator design increased the cooldown time (from room temperature to 73K) by approximately 50 seconds (at 4 min. 45 sec), but a moderate gain in cooling capacity was observed. The benefit of cooling capacity is more pronounced at low coldtip temperature and high ambient. Since in most applications, the required cooldown time is around 6 minutes, BEI decided to adopt the new regenerator design to take advantage of the extra cooling capacity.

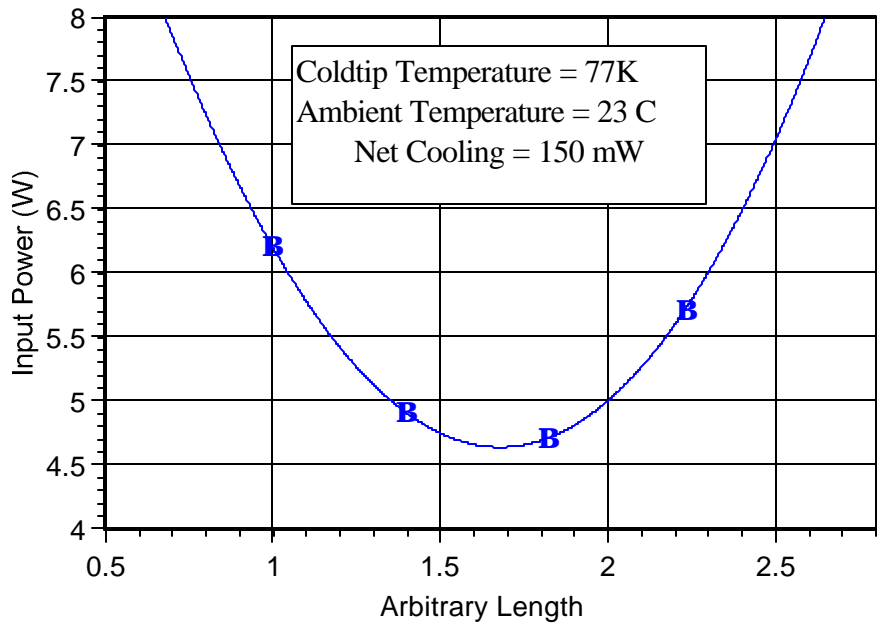


Figure 1. Effect of Regenerator Length.

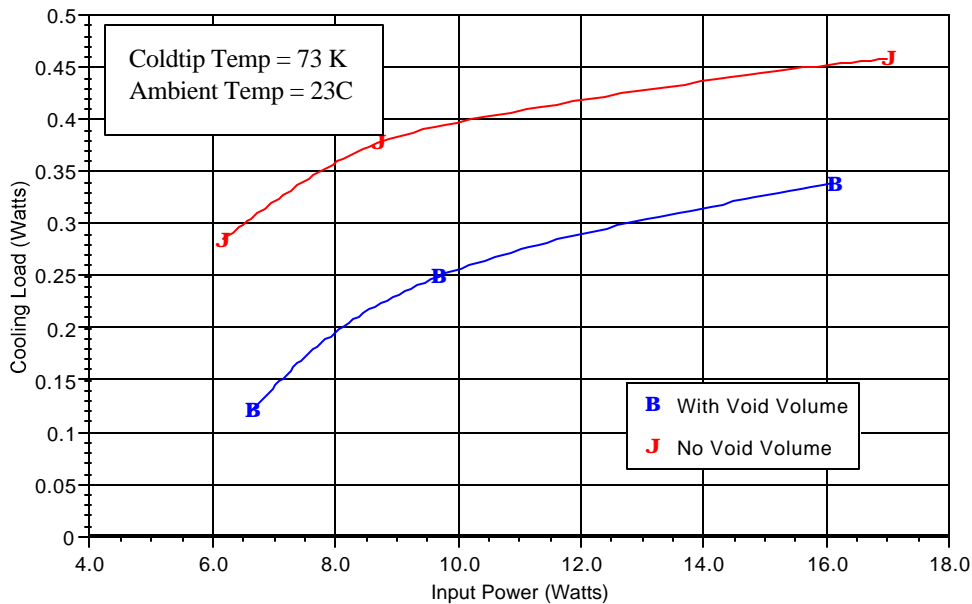


Figure 2. Effect of Dead Volume.

MOTOR PERFORMANCE

The performance of a motor depends on the motor efficiency, the presence of dead volume, and the size of the clearance gap of the piston. Excessive dead volume decreases the pressure ratio thus degrades the performance. This effect is shown in Figure 2, and is more pronounced at small input powers.

It is a well-known fact that blow-by losses across the piston clearance gap tend to reduce the useful work of the compressor.

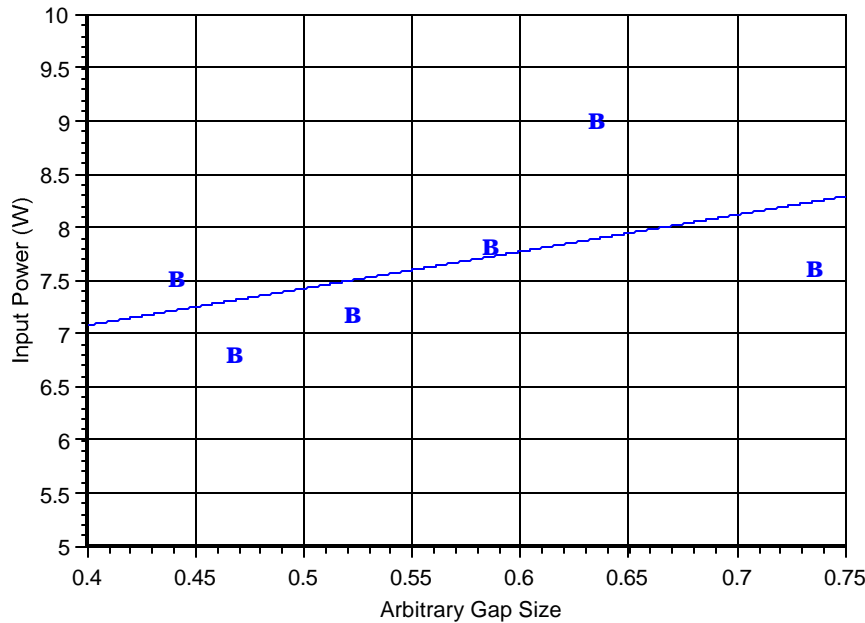


Figure 3. Input power versus piston gap size.

The mass flow of the helium gas in the piston clearance gap is governed by the following equation,

$$\dot{m} = \frac{\rho D S^3}{32} \frac{r \Delta P}{h L} \quad (1)$$

where S is the radial gap of the piston clearance, D is the piston diameter, L is the gap length, ΔP is the pressure drop, ρ is the density and η is the viscosity of the helium gas. From the above equation, one can see that the blow-by flow across the clearance gap is a strong function of the gap size.

Figure 3 shows the input power of the cooler as a function of the piston clearance gap. Within data scatter and limited data studied, a correlation can be seen between the gap size and input power, favoring smaller gap size for better performance.

Three prototype high performance compressors (C1751, C1752, and C1753) were built and tested. The result of these tests can be found in Column 4 of Table 1. The new compressor design improves the cooldown time (to 73K) by approximately 10 seconds and consumes about 3 watts less power at 73K, with an ambient temperature of 60C. The decrease in input power is less at room temperature (~2.3 Watts).

REDUCE PARASITIC HEAT LOSSES:

Another important area in enhancing cooler performance is the reduction of parasitic heat losses. Parasitic heat losses include heat conduction along coldfinger and regenerator shell, pressure drop loss, shuttle and/or blow-by losses in the displacer gap, and pumping loss. The BEI high-performance cooler contains enhancement in one or more of the above areas.

Comparing the fifth column to the fourth column, one can see that approximately 1 Watt decrease in input power is resulted by reducing the parasitic heat loss.

RESULTS

The experimental results of the high-performance cooler with enhanced regenerator, motor efficiency, and reduced parasitic heat loss are listed in the fifth column of Table 1. From left to right, Table 1 shows the progressional enhancement of experimental performance due to the above study. The new cooler is approximately 3 Watts lower in input power with 150 mW heat load at room temperature, when compared to the old baseline. The enhancement is approximately 4 Watts at high ambient.

The typical cooldown characteristic of the enhanced cooler is shown in Figure 4 for ambient temperatures of -41C, 23C and 71C. The cooldown time to 73K is less than 5 minutes at room temperature and approximately 10 minutes at 71C.

Figure 5 shows the input power as a function of refrigeration capacity. The cooler provides close to 500mW of cooling at 78K with 15 Watts of input power. The coldtip temperature as a function of refrigeration capacity is plotted in Figure 6.

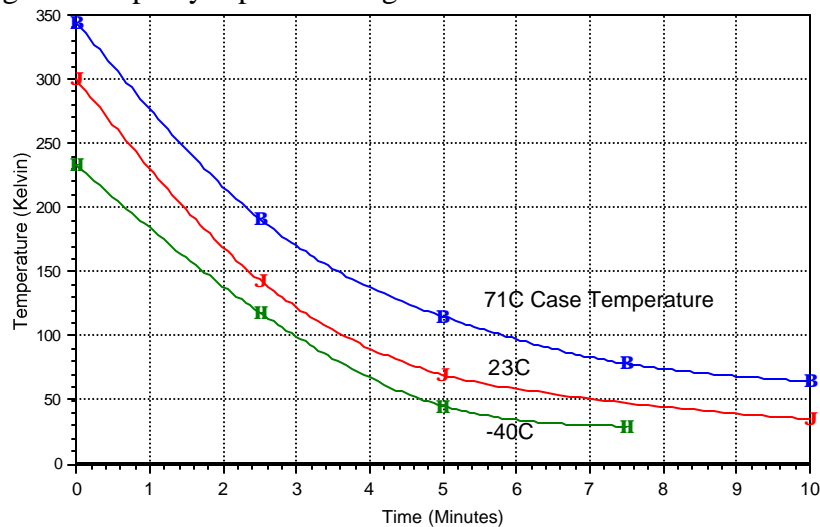


Figure 4. Cooldown time as a function of time.

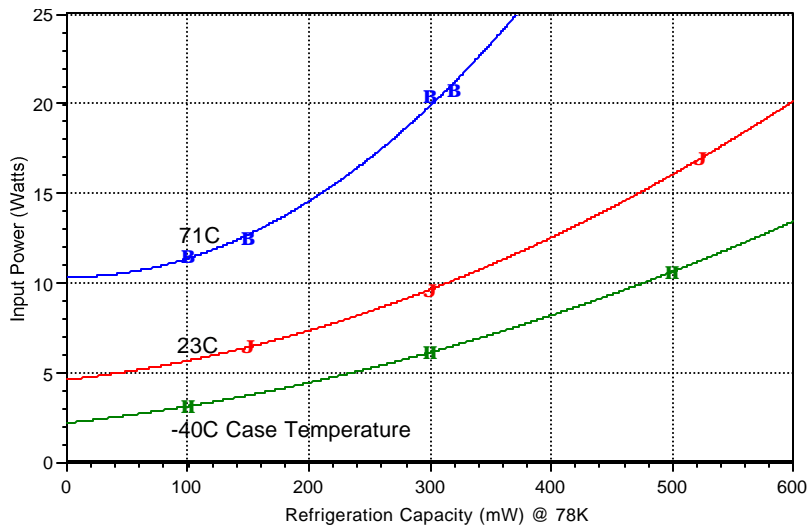


Figure 5. Input power as a function of refrigeration capacity.

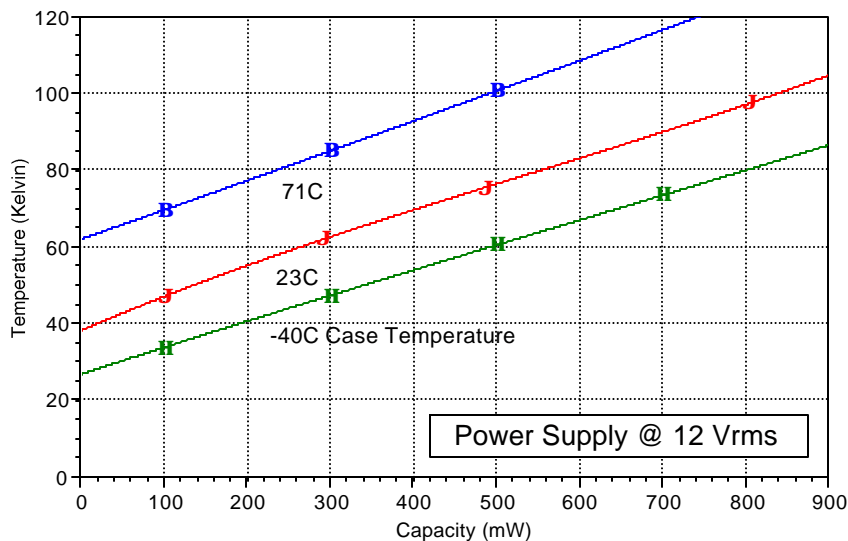


Figure 6. Coldtip temperature as a function of refrigeration capacity.

CONCLUSIONS

A 73K High-Performance Cooler has been analyzed, designed, fabricated and tested at BEI, which delivers 150 mW of cooling with a mere input power of 10.5 W at 60C ambient, and 7.1 W at 23C. The cooldown time to 73K is approximately 4 minutes and 20 seconds. At 78K, the input power is 6.3W for a heat load of 150mW at 23C ambient.

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