

# Ribbon Regenerator Performance in a Single-Stage GM Cryocooler

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## ABSTRACT

The need to operate a single stage, regenerative cryocooler near 20K with some significant capacity is of great interest to the high temperature superconductivity industry. One method is to improve the performance of the regenerative heat exchanger. A regenerator was fabricated as a ribbon with embossed ridges across the width of the ribbon and coiled in a jelly-roll configuration. These thin pancakes are then stacked one on top of the other to provide the desired length of the regenerator. Materials used to fabricate these regenerators were Bronze, Lead, and Holmium for high heat capacity at the lower temperatures. Performance of these regenerators was measured using a CTI 350, single stage GM cryocooler and compared to the screen geometries. Results indicated that the screen geometry performed slightly better than the ribbon.

The fabrication of the Holmium ribbon proved to be difficult and therefore the increase in performance using Holmium could not be measured.

## INTRODUCTION

In the past few years, the high temperature superconducting industry has developed a great need for a cooler that can provide cooling in the 20-30K temperature range. Typically, GM coolers have been limited to a no-load temperature of about 26 K in a single stage and have limited cooling capacity at 30 K. Some coolers have demonstrated improved lower-temperature performance by using lead spheres in the cold end of the regenerator, but cryocooler capacity is still low.

It is clear that a regenerator that has lower losses and a higher heat capacity is needed. One regenerator geometry to reduce the pressure drop losses is an embossed ribbon regenerator. This type of regenerator can be fabricated from a variety of high heat capacity materials using a rolling mill to emboss ridges on one side of the ribbon. In addition, a ribbon regenerator can be formed to optimize its performance by varying several of its flow and thermal characteristics. Some of these characteristics are as follows:

- Reduced pressure drop losses
- Vary its void volume
- Reduce the conduction losses
- Maximize the heat transfer area
- Use materials with high heat capacity at different temperatures

However, these characteristics are not all independent of one another, and many are limited by other characteristics or fabrication difficulties. Thus, the regenerator design needs to be optimized to

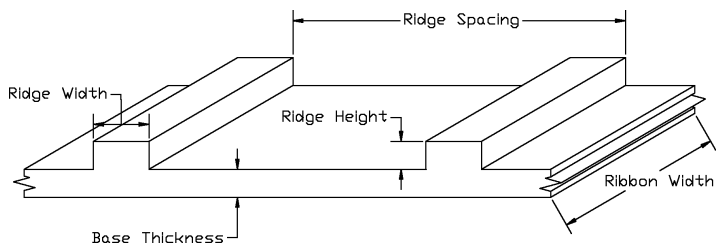


Figure 1. Embossed ribbon geometry.

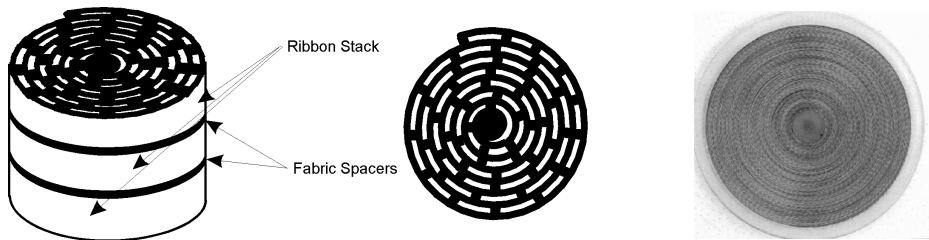


Figure 2. Ribbon regenerator assembly (left) and photo of final product (right).

meet of the application and the cryocooler being used. A Neodymium ribbon regenerator was designed and tested in a 2-stage GM by Green<sup>1,2</sup> and Chafe and produced good results.

Figure 1 shows the embossed ribbon geometry that was used in this study and the dimension variables that can be changed to optimize the regenerator ribbon. The ribbon dimensions are fabricated based on the grooves machined into the rolling mill and the methods used in forming the ribbon. A process then results in a continuous length of embossed ribbon. This ribbon is then wound in the form of a jellyroll pancake and stacked one on top of the other to give the desired length of the regenerator. Figure 2 shows the assembly of the jellyroll regenerator using the embossed ribbon. Felmley<sup>3</sup> reported on some of the material characteristics of forming the ribbon with Neodymium.

The other factor that makes the ribbon regenerator attractive is the fact that any ductile, high heat capacity material can be fabricated into this geometry. Metals like lead, holmium, erbium, and ductile alloys of the rare earth metals developed by Iowa State University Research can be rolled into a ribbon geometry. Figure 3 compares the heat capacity of Holmium to the traditional Stainless Steel and Phosphor bronze screen regenerator material. It should be noted the higher heat capacity of Holmium at temperatures below 100 K. Ribbon regenerators using higher heat capacity material

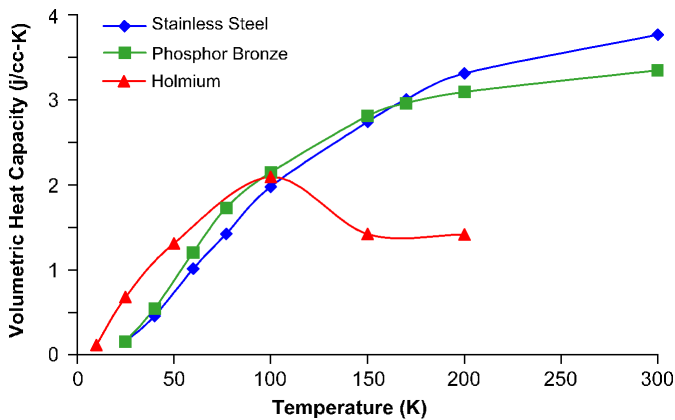
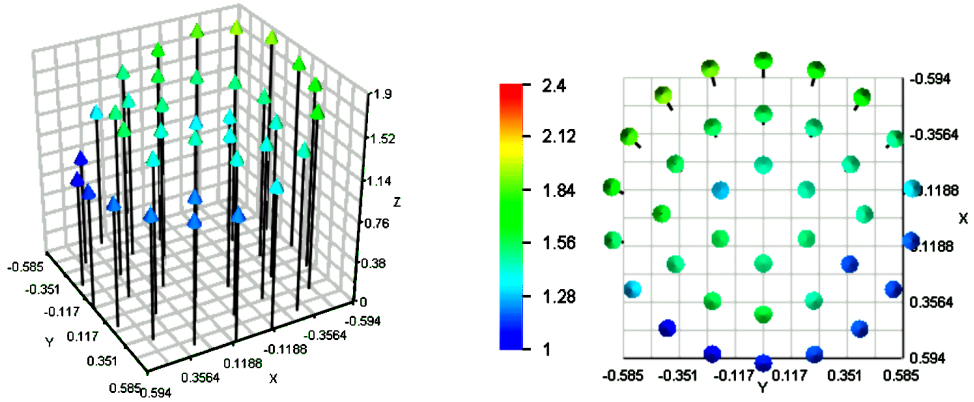
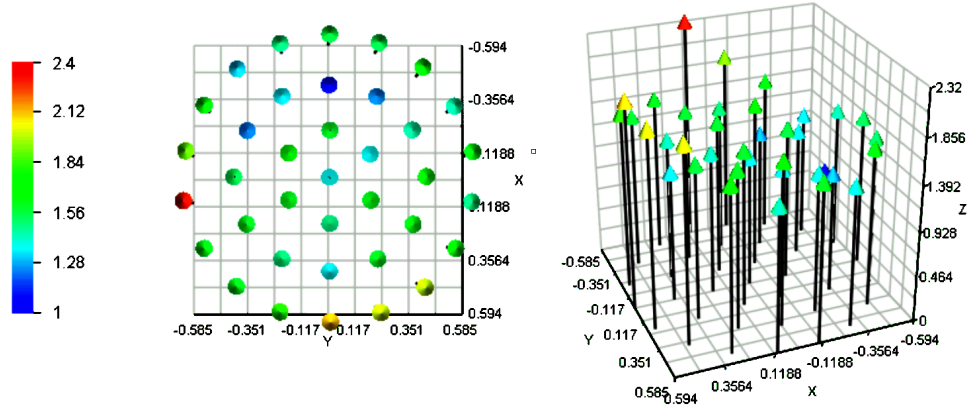


Figure 3. Volumetric heat capacity of some regenerator materials.



**Figure 4.** Velocity distribution (m/s) at the exit of a single ribbon coil.



**Figure 5.** Velocity (m/s) profiles for a stack of 10 woven screens.

have the potential for greater capacities and lower temperatures. This study will measure the potential losses for the ribbon regenerator design and compare its performance in a GM cryocooler.

### FLOW UNIFORMITY TESTS

The flow uniformity measurements were made for steady flow through a single coil and a stack of ten screens. These measurements were made with a pitot static probe and a differential pressure transducer. The velocity is then derived from the pressure reading using Eq. 1.

$$Velocity = \sqrt{\frac{2\Delta p}{\rho}} \quad \text{Where : } \Delta p = \text{pressure differential} \quad (1)$$

$$\rho = \text{density}$$

Since density variation over the cross-section will not occur due to low Mach numbers, the velocity at a point is directly proportional to the mass flow. Thus, the velocity distribution plots are equivalent to the mass flow distribution. These data are shown in Figure 4 for the ribbon matrix and in Figure 5 for the stacked screens.

Velocity in the 3D plots is on the z-axis and is also indicated by the color scale. The right hand plot shows an axial view illustrating the spatial relationship of the data points. Basic analysis is shown in Table 1. The calculated mass flow using the velocity profile and the measured mass flow using a variable-area flow meter shows good agreement. This indicates that the pressure measurements and subsequent velocity calculations are consistent.

**Table 1.** Average and standard deviation of velocity measurements made at the exit of a regenerator packed with 10 screens and a single ribbon coil.

Matrix Geometry	Average Velocity	Standard Deviation
Ribbon (one coil)	1.47 m/s	0.22 m/s
Screen (stack of 10)	1.59 m/s	0.24 m/s

**Table 2.** Ribbon and screen regenerators.

Properties	Embossed Ribbon(R2.594)	200 Mesh Screen(S5.699)
Mass(g)	226	168
Void Volume(cc)	0.594	0.698
Surface Area(cm <sup>2</sup> )	6,163	16,812
Hydraulic Diameter(cm)	0.0195	0.0104

The results of this test indicated that the flow distribution through the ribbon regenerator provided better uniformity than the screen regenerator.

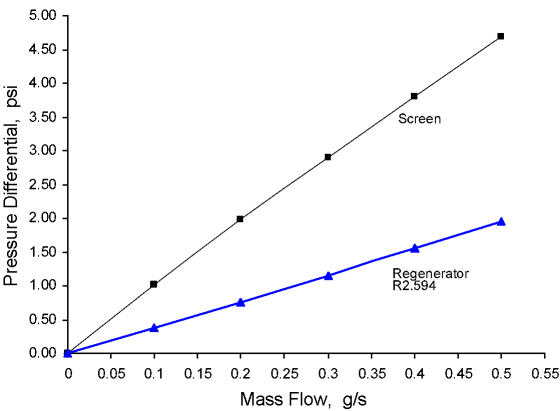
**PRESSURE DROP MEASUREMENTS**

Two regenerators were fabricated, the first a 200 mesh screen regenerator (S5.699) and the other a ribbon regenerator (R2.594) with a ribbon width of 2.59 mm. Table 2 lists some of the critical properties of these two regenerators.

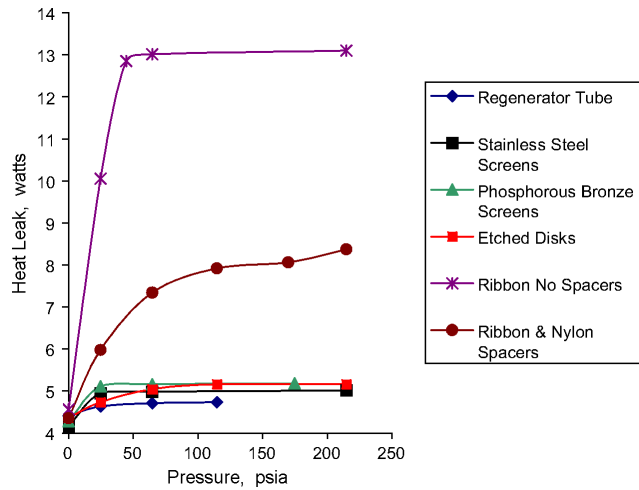
A steady flow of helium gas was passed through each regenerator matrix and the pressure drop across the regenerator was measured. Figure 6 shows the pressure drop as a function of the mass flow. Results indicate the ribbon regenerator has a significantly lower pressure drop than the 200 mesh screen regenerator.

**CONDUCTION HEAT LEAK TESTS**

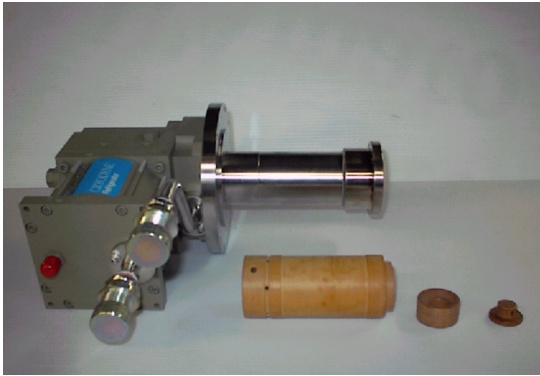
The heat leak for a ribbon regenerator and a screen regenerator were measured using liquid Nitrogen as the low temperature sink. The tests on the thermal conductivity measurements of the screen and ribbon regenerators are discussed in a paper by Superczynski.<sup>4</sup> Results of these measurements are shown in Figure 7 and show that a ribbon regenerator results in a significantly higher heat leak than a screen regenerator. A 60% higher heat leak was measured with a ribbon regenerator using the same dimensions as was used in the screen regenerator. These results clearly indicate the design of a ribbon regenerator needs to be different than that of a screen regenerator. A ribbon



**Figure 6.** Pressure drop measurements for a ribbon and screen regenerator.



**Figure 7.** Heat leak for various regenerator materials and geometries.



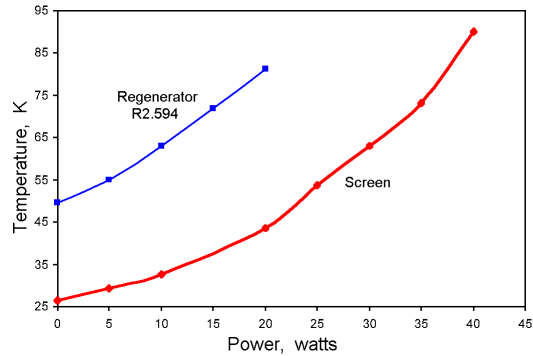
**Figure 8.** CTI Model 350 and regenerator housing.

regenerator has a high conduction loss and a low pressure drop, it would appear that one solution would be to make the length/diameter ratio larger for a ribbon regenerator than for a screen regenerator.

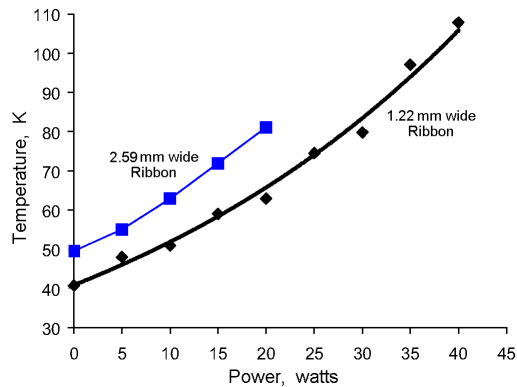
**COOLER PERFORMANCE TESTS**

A CTI cryocooler system (model 350 coldhead and 8200 compressor) was used to measure the performance of the screen and ribbon regenerator. A 200-mesh screen regenerator used in this commercial cryocooler provided a baseline for the cooler. Figure 8 shows this single stage cooler and its regenerator housing. The regenerator housing was modified to allow the replacement of the regenerator material. A pin was installed at the cold end of the regenerator to replace the screen regenerator matrix with ribbon.

Measuring the performance of the cooler required a heater and temperature sensor to be attached to the cold tip. To provide a method of attaching these test elements, a copper plate was fabricated which bolted to the cold tip. A thermofoil™ heater, which consists of a flexible etched foil resistive element laminated between two layers of Kapton insulation, is clamped between the cold tip and this plate. Two temperature sensors were mounted to the copper plate for redundancy. Both sensors were in agreement throughout the testing. All thermal contact areas were coated with Apiezon N™ grease to minimize the temperature gradients across these interfaces.



**Figure 9.** GM cooler performance with a screen and ribbon regenerator.



**Figure 10.** GM cooler performance with a ribbon regenerator.

Performance of the screen regenerator was first measured and verified that it produced the cooling capacity published by CTI. The screen regenerator was then replaced by a ribbon regenerator(R2.594). The results of these measurements are indicated in Figure 9 and indicated a lower performance than was obtained with the original screen regenerator. In fact, a no load temperature of 49 K was obtained with the ribbon regenerator. It was noted that several critical parameters were lower for the ribbon regenerator than what was used in the screen regenerator, most notably the heat transfer area and the conduction heat leak.

The regenerator housing was modified by machining 18% more length from the regenerator space and by fabricating a ribbon with half the width as the original ribbon. A new regenerator was assembled into the CTI cryocooler and the performance measured. Figure 10 indicates the improved performance with the 1.22 mm wide ribbon regenerator.

The cooler performance clearly indicates that the regenerator has not been optimized and the ribbon regenerator needs to be designed for use in a single stage GM cooler.

**HOLMIUM RIBBON FABRICATION**

The next step was to fabricate ribbon from material with high heat capacity below 100K. Holmium was selected due to its high heat capacity between 100-20 K. A 2 kg cast bar of Holmium with a purity of 99.9% was purchased from Santoku America, Inc. This Holmium bar was then sent to Supercon, Inc. to draw the Holmium bar into a continuous length of 0.055 inch diameter wire, similar to that done with Neodymium.<sup>5</sup> Due to its unknown wire drawing characteristics, Supercon elected to use only half of the material in its initial wire drawing attempt. Titanium was used to provide an etching barrier and a thin copper layer surrounded the Holmium bar. The copper layer protected the

Holmium from oxidizing during the drawing process at the higher temperatures, and the copper was later etched off the wire. This first attempt at forming the wire was very successful and produced 0.055 inch diameter wire in a continuous length.

The second half of the Holmium bar was processed in a similar manner. Unfortunately, the Titanium barrier failed and intermetallic compound formed with the copper. This intermetallic compound formed at various points in the wire, making it brittle, and the wire broke into several short lengths. The short lengths of wire produced from the second half of the material made the wire useless to wind in a regenerator.

The first batch of holmium wire was sent to Concurrent Technology Corporation (CTC) to be fabricated into embossed ribbon. Initial attempts to roll Holmium resulted in severe embrittlement and subsequent edge cracking. Attempts to anneal the Holmium wire were unsuccessful and CTC could not fabricate the embossed holmium ribbon.

## SUMMARY AND CONCLUSIONS

Stainless steel, phosphor bronze, and lead embossed ribbons were fabricated and tested in a CTI 350 single stage GM cryocooler. Separate tests were conducted using these regenerators to evaluate flow uniformity, pressure drop, and conduction heat leak. The ribbon did not perform as well as the screen regenerator when placed in the standard CTI 350 regenerator holder. After modifying the regenerator holder and fabricating a narrower ribbon, a significant improvement in the cooler performance resulted. It is concluded from these tests that the ribbon regenerator cannot be expected to perform as well as a direct replacement for a screen regenerator.

The ribbon regenerator has many dimensional variables that can be adjusted to provide lower conduction losses, higher heat transfer surface, lower dead volume, and lower flow losses. In addition, the length/diameter ratio of the regenerator should be adjusted to optimize the performance of the regenerator. This length/diameter ratio for the ribbon should be very different than that used for a screen regenerator.

Another benefit of the ribbon regenerator is the use of higher heat capacity materials at the lower temperatures. In fact, a ribbon regenerator is able to optimize the heat capacity of the regenerator to maximize the performance of the cooler.

## ACKNOWLEDGEMENTS

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