Results of Tests of Etched Foil Regenerator Material

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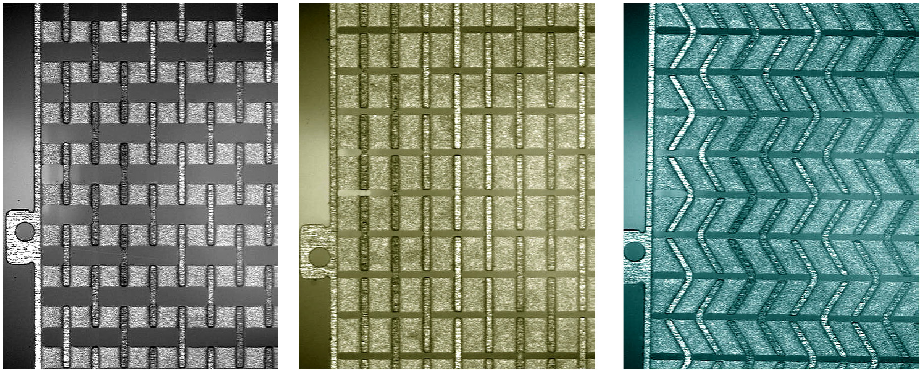
ABSTRACT

A parallel-plate regenerator fabricated by Mitchell/Stirling from flat-stacked layers of etched stainless steel foil was tested at Sunpower, Inc., under a grant from NASA Glenn Research Center to Cleveland State University, in a regenerator test rig on loan from NASA. Test data were analyzed by Gedeon Associates. The tests of the etched stainless steel foil regenerator were part of a program of tests of a variety of regenerator materials and geometries. From Reynolds numbers 40 to 200, the figure of merit ("F_M") for the etched stainless steel foil regenerator was higher than for screens or random fiber of 70% porosity, or packed spheres of 39% porosity. Porosity of the foil regenerator tested was 55%. The F_M measures the heat-transfer effectiveness per unit of flow resistance. The substantially greater thermal mass of the foil regenerator, coupled with its superior F_M suggests that the tested foil regenerator is superior to screens of 70% porosity for cryocooler applications. Although the thermal mass of packed spheres of 39% porosity is high, the low F_M of packed spheres suggests that they are not competitive with the other materials except at very low temperatures. The flow path through the foil regenerator as tested was straight-through. Another foil regenerator with similar porosity but with a zigzag flow path remains to be tested. Previous experimental work under less rigorous conditions suggests advantages of the zigzag flow path in annular regenerators.

TEST SAMPLES

The foil regenerators assembled for testing were etched in three distinct patterns as shown in Figure 1. The sample tested so far is the pattern designated "2A", which permits straight-through flow from one end of the regenerator to the other between 52 sets of parallel plates. Flow channels are etched about 0.045 mm deep into the front side of foil with a nominal thickness of 0.0762 mm.

Cryocoolers 14, edited by S.D. Miller and R.G. Ross, Jr.



1A. 2A 3A

Figure 1. Etch patterns in regenerator foils

Flow is vertical in the channels as shown above**.** Channels normal to the flow direction are etched into the back side of each foil, also to a depth of about 0.045 mm. Where the channels on the front and back sides of the foil meet, there are holes in the foil. The overall effect is a lacework of parallel plates held together by periodic spacer-bridges.

Selection of sample patterns

The rationale for the selection of sample patterns was twofold. The two straight-through patterns offered an opportunity to determine whether an etched foil regenerator could deliver the performance advantage suggested by the literature for a parallel plate arrangement. Although excellent results had been obtained in some prior work with parallel plates[1], there was doubt as to whether the etching process could be precise enough to realize those advantages in practice.[1,2]

The rationale for the zigzag pattern was prior experience with annular etched foil regenerators in an experimental cryocooler originally designed to test a different concept.[3] Comparison of the results with three different patterns of regenerator foil in the regenerator of a concentric pulse tube cooler had demonstrated that a severe zigzag pattern appeared to distribute flow in the regenerator evenly around its circumference, dramatically improving cooling.[3]

In pattern 3A, the flow channels follow a zigzag path down the front side of the foil. The other two samples have straight flow channels. The difference between the two samples with straight-through flow patterns is in the widths of the parallel plates and the spaces between them. All foils have 52 plates from end to end. In two denser samples, (the zigzag sample and the denser of the two straight-through samples) the plates are 0.787 mm wide in the flow direction and are separated by gaps of 0.178 mm. In the other sample the plates are 0.483 mm wide and are separated by gaps of the same size.

About 218 layers of each of the three patterns of foil were stacked flat and inserted into sabots through which square holes had been broached. The cross section of the assembled regenerators is square, nominally 16.61 mm on a side. Details of the assembly procedure are contained in an earlier paper published in the proceedings of the 2005 International Energy Conversion Engineering Conference.[4] When the foil layers are perfectly aligned in a stack, they are in registration with each other. The flow thus passes through a serious of grids of parallel plates separated by spaces that are largely void. The only metal in the spaces that separate the grids consists of the spacer-bridges, which occupy only about 4% of the volume and which provide a very constricted thermal conduction path between successive grids.

Figure 2 shows a portion of the end of the denser straight-through regenerator in its sabot. The photograph was taken at NASA Glenn Research Center. Similar photographic analysis showed that the zigzag foil sample and the less dense of the two straight-through samples were less than perfectly aligned. On that basis, the denser straight-through sample was selected for the first test.

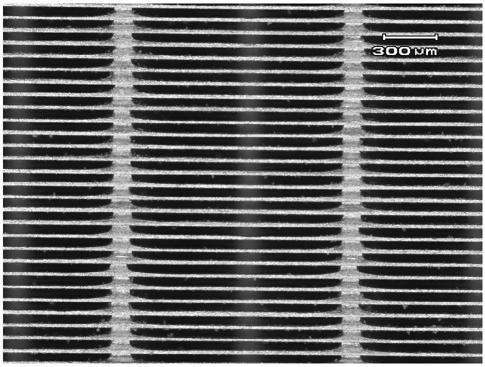


Figure 2. Close-up of the end of the tested regenerator.

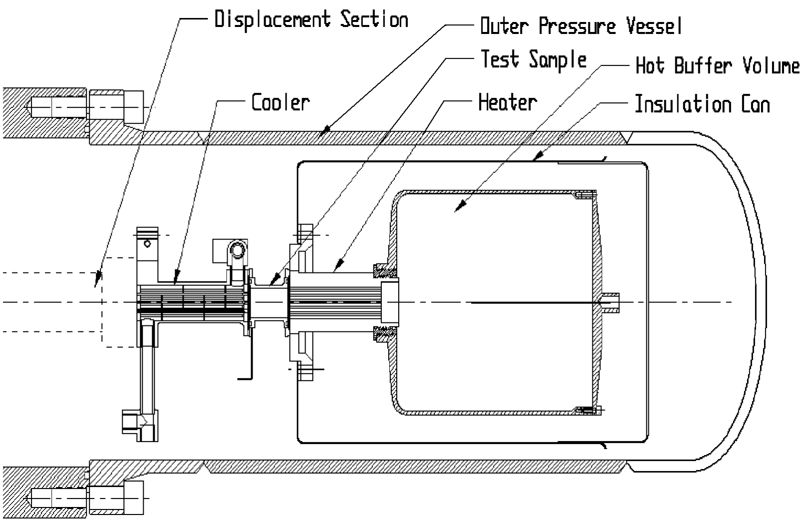


Figure 3. NASA/Sunpower test rig.

Test Apparatus

Testing was conducted in an oscillating flow test rig operated by Sunpower, Inc., for NASA Glenn Research Center. The apparatus is shown in Figure 3. The NASA/Sunpower regenerator test apparatus generates fundamental heat-transfer and pressure drop information as a function of Reynolds number under oscillating flow conditions.

A linear compressor generates an oscillating flow between the compression space and an insulated buffer space. The test regenerator is clamped between a water-jacketed cooler adjacent to the compressor and an electrically-heated heater section adjacent to the buffer volume. The insulated buffer volume is hot. The buffer is large enough so that there is little pressure change over the cycle.

Both ends of the regenerator are instrumented with thermocouples and pressure transducers. The data acquisition system records real time pressure data and time-averaged temperature data. Piston amplitude and heat rejected to the water passing through the water jacket of the cooler are likewise measured and recorded.

To obtain a first-cut figure of merit for a regenerator, three parameters are calculated from the data for a range of Reynolds numbers:

1. Darcy friction factor;
2. Nu, the Nusselt number, a measure of heat transfer effectiveness; and
3. Nk, a measure of thermal dispersion.

Table 1. Charge fluids and pressures for test cases.

Gas	P_{charge} (bar)
nitrogen	50
nitrogen	25
nitrogen	10
helium	50
helium	25
helium	10

The Reynolds number is calculated conventionally, from fluid velocity and viscosity, using the hydraulic diameter calculated as a function of dead volume and wetted surface of flow passages.

Nu and Nk are determined by analysis of the extra heat rejected to the cooler water jacket as each case is run. (Baseline heat leakage through the regenerator, its housing, clamping screws, data acquisition wires, etc., is obtained with the heater and cooler at operating temperature but the piston at rest). When the piston begins to move, the heat leakage increases as a result of incomplete heat transfer between fluid and regenerator matrix and an increase in "thermal dispersion" representing an alternative method of heat transport attributed to the transport of thermal energy due to micro-scale velocity and temperature fluctuations. Responsibility for excess heat leakage is distributed between Nu and Nk using curve-fitting data reduction software.

Test program

To obtain a range of Reynolds numbers, six distinct test cases were run, with the rig charged with nitrogen and helium at three different charge pressures, as shown in Table 1.

For each test case, the piston amplitude was swept up and down twice across a range of amplitudes. For each piston amplitude, data points were logged after the rig reached a periodic steady state. Each test case took about a day to run.

The test cases cover a wide range of Reynolds numbers, with the lowest corresponding to the lowest piston amplitude with 10 bar helium and the highest corresponding to the 50 bar nitrogen test with the largest piston amplitude. The foil sample was tested at Reynolds numbers ranging from 1.5 to 1200.

It is important to be accurate at the low end of the Reynolds number scale, because that is where most cryocooler regenerators operate. The most important data are for a range of Reynolds numbers bounded by about 200 on the high side, and 20 on the low side. In cryocooler regenerators, Reynolds numbers typically peak below 200. Below 20, not much fluid is flowing. Accurate Reynolds-number data help in the data reduction of simultaneous N_u and N_k numbers. Data at the two extremes of Reynolds number are necessary to resolve the two because the effects of N_u are relatively more important at high Reynolds number, and the effects of N_k are relatively more important at low Reynolds numbers.

To bring all of the data into sharp focus, a single "figure of merit" ("FM") was calculated for a range of Reynolds numbers. The calculation is as follows:

$$F_m = \frac{1}{f\left(\frac{P_e}{4N_u} + \frac{N_k}{P_e}\right)} \qquad (1)$$

where

f = Darcy friction factor; and

Pe = Peclet number = Reynolds number times Prandtl number.

Even though gathered at room temperature and temperatures above, the data collected, coupled with material property information, form the complete basis for the computational model used in the Sage computer program. There is no problem extrapolating Sage predictions to cryogenic operating conditions as long as the range of Reynolds numbers, etc., in the test procedure covers the range in cryogenic operation.

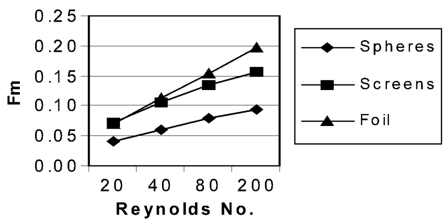


Figure 4. Figures of merit for selected cryocooler regenerator materials.

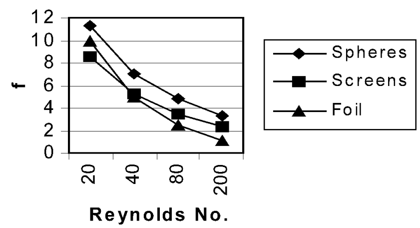


Figure 5. Darcy friction factor (f in figure of merit formula).

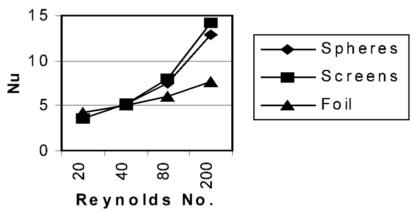


Figure 6. Nusselt number (N_U in figure of merit formula).

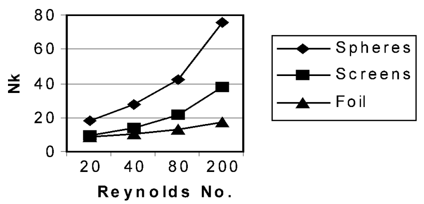


Figure 7. Thermal dispersion (N_K in figure of merit formula).

TEST RESULTS

Taking everything into account, the overall F_M for the etched-foil regenerator sample was substantially better than for 70% porosity screens or 39% porosity packed spheres as shown in Figure 4. Random fiber of 70% porosity, also tested but not shown here, was found to have an F_M slightly inferior to 70% porosity screens.

That F_M emerged from the Darcy friction factor, Nu and Nk readings from the test program. As shown in Figure 5, the Darcy friction factor for foil was substantially lower than for screen or packed spheres at and above a Reynolds number of 40. There were also significant differences between foil on the one hand, and spheres and screens on the other hand, with respect to both N_u and N_k values; in each instance, the foil sample scored lower than the other two samples at all Reynolds numbers above 40 as shown in Figures 6 and 7.

Combining the readings for f, Nu and Nk in accordance with the figure of merit equation above, the foil came out on top. At a Reynolds number of 200, the etched-foil F_M is about 0.198 compared to about 0.157 for 70% porosity screens, 0.094 for 39% porosity packed spheres, and 0.093 for 70% porosity screens or random fibers.

Those figures of merit suggest that a Stirling cooler fully optimized to use an etched foil regenerator should have an edge in efficiency compared to a comparable machine optimized for an alternate regenerator — though not in proportion to its figure of merit, because the regenerator is only part of the whole picture. Previous Sage optimization studies for an ideal parallel-plate regenerator with an F_M about three times higher than random fibers gave an overall efficiency improvement on the order of only 10% in a 100 W size space power engine. However, the predicted impact of improved regenerator performance on coolers, as distinguished from prime movers, remains to be examined in detail.

There are two other aspects of cryocooler regenerator effectiveness that must be considered. First, with a cooler, the thermal mass of the regenerator is much more important than in an engine due to the higher heat capacity of the cold fluid and the lower heat capacity of the regenerator material at temperatures below about 40 K. For a given compressor displacement, approximately the same dead volume will be required for a cooler's regenerator, regardless of its structure. For a given dead volume in the regenerator, packed spheres, with a porosity of 39% offer the largest thermal mass (and require the largest housing). With the same dead volume, screens or random fibers of 70%

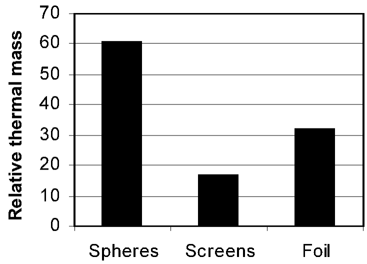


Figure 8. Relative heat capacities of regenerator structures with equal dead volumes.

porosity provide the smallest thermal mass. The foil, as tested at a porosity of 55%, offers intermediate thermal mass. The relationship is shown in Figure 8.

That relationship would seem to favor spheres, leaving foil behind, and screens far behind. However, when the relative figures of merit of the three are considered, foil would appear to be the superior choice. The F_M for foil is more than twice that of spheres and significantly greater than that of screens or random fibers with 70% porosity. Regenerators with higher porosity would appear to be inappropriate for cryocoolers due to their inadequate thermal mass.

Another aspect of regenerator design has to do with circulation. There are strong indications that regenerators tend to develop circulation in which warm flow predominates in one part of the regenerator and cold flow in another. That imbalance has a very marked influence on cooler performance. One of the clearest demonstrations of the tendency toward circulation was reported by Kirkconnell.[5] The regenerator in question was divided into three parallel tubes, all nominally identical in construction and flow regime. In operation, the three tubes developed major disparities in midpoint temperature and cooling performance was disappointing. When the midpoints of the three regenerators were tied by a thermal strap to minimize that temperature difference, performance improved significantly.

Similar imbalance in flow (and adverse impact on cooling performance) was reported previously by Mitchell and Fabris in an annular regenerator surrounding a pulse tube.[3] The problem was corrected, and performance greatly improved, using a zigzag etch pattern in the foil. That pattern generated circumferential flow on the back side of the foil driven by the main, axial flow through the zigzag channels on the front side of the foil. The implications of the zigzag flow arrangement remain to be tested in the NASA/Sunpower rig. However, the full benefits of more uniform flow distribution in the regenerator probably will not be reflected in the F_M, if and when the zigzag sample is tested in the NASA/Sunpower rig, since flow distribution in that rig is already quite good.

For regenerators with the same flow areas, the F_M is inversely proportional to the product of pumping loss and thermal loss. Thus, a high figure of merit will correspond to a low pumping loss, a low thermal loss, or both. But depending on the relative sizes and importance of the two losses in an actual cryocooler, the overall benefit to cooler efficiency will vary. In the comparative tests reported above, the superior F_M of the foil regenerator resulted in significant part from its low friction factor — about one third of the value for spheres, and less than half the value measured for 70% porosity screens at Re=200. Although it had the lowest Nu value at Re = 40 and above, the foil regenerator had the most advantageous ratio of Nu to Nk over the whole range as shown in Figure 6. At Re = 200, the ratio was 0.45 for foil, as compared to 0.37 for screens, and 0.17 for spheres.

CONCLUSIONS

Tests conducted on a flat-stacked etched foil regenerator of about 55% porosity, at temperatures at and above ambient, produced a maximum figure of merit substantially greater than that for packed spheres of 39% porosity or for screens or random fiber of 70% porosity in the most relevant range of Reynolds numbers. The figure of merit reflects both the pressure drop and heat transfer characteristics of the regenerator, and is a useful first cut at regenerator analysis. Results of those tests can be directly translated to cryocooler regenerators through their associated Reynolds numbers. Taking into account the thermal mass associated with the porosities of these different regenerator structures, the etched foil appears to be the superior structure for cryocooler applications.

Previous experimental work with several different patterns of etched regenerator foil in a cryocooler suggests that a zigzag flow path may be superior to the straight-through flow path of the tested sample. Further testing effort appears to be warranted.

ACKNOWLEDGMENT

Acquisition and testing of the regenerator material described here was funded by Science Mission Directorate and the Radioisotope Power Systems Program at NASA Glenn Research Center. Any opinions, findings and conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the view of the National Aeronautics and Space Administration.

REFERENCES

1. Backhaus, S., and Swift, G. "Fabrication and Use of Parallel Plate Regenerators in Thermoacoustic Engines," *Proceedings of the 36th Intersociety Energy Conversion Engineering Conference*, Vol. 1, ASME, New York (2002), pp. 453-458.
2. Gedeon, D., "Flow Circulation in Foil-Type Regenerators Produced by Non-Uniform Layer Spacing," *Cryocoolers 13*, Springer, New York, 2005, pp. 421-430.
3. Mitchell, M.P. and Fabris, D., "Improved Flow Patterns in Etched Foil Regenerators," *Cryocoolers 12*, Kluwer Academic/Plenum Publishers, New York (2003), pp. 499-505.
4. Mitchell, M.P., Gedeon, D., Wood, G. and Ibrahim, M., "Testing Program for Etched Foil Regenerator Material," *Proc. 3d International Energy Conversion Engineering Conference*, (2005), AIAA Paper 2005-5515, CD ROM #18.
5. Kirkconnell, C.S., "Experimental Investigation of a Unique Pulse Tube Expander Design," *Cryocoolers 10*, Kluwer Academic/Plenum Publishers, New York, (1999), pp. 239-247.