Measurement of Heat Conduction through Bonded Regenerator Matrix Materials

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ABSTRACT

Regenerative heat exchangers have had a significant influence on the development of small refrigerators for cryogenic applications. The optimized design of these regenerators takes into account the axial thermal conduction of the matrix. Until recently this thermal conduction has been unknown even for the commonly used screen or packed sphere matrices. Research at NIST on the thermal conduction through such matrices has shown that the thermal conduction is best represented by a thermal conductivity degradation factor. We have given this factor previously for stacked metal screens of various mesh and porosities and for packed spheres of various metals. This factor is important in optimizing the geometry of the stacked screens or packed spheres. In this paper we discuss the measurements of the thermal conduction in regenerator matrices when they are bonded either by sintering or with the use of thinned epoxy. Such bonded matrices offer some advantages in the fabrication of regenerators. For example, the uniform stacking of large diameter screen matrices with negligible gaps around the circumference can be difficult to achieve. Also, the containment of fine metal powders can be difficult. The bonding of these matrices can solve many of these fabrication problems, but could possibly be a disadvantage because of enhanced thermal conduction. Experimental results with diffusion-bonded 325-mesh stainless steel screen and epoxy-coated lead spheres are presented in this paper. The results show only a small increase in thermal conduction, which does not significantly affect the overall cryocooler performance.

INTRODUCTION

The use of stacked stainless steel screens and packed beds of lead spherical material are commonly used in the design of cryocooler regenerators.[1] Research has been done at NIST on the thermal conductivity characteristics of some of the more commonly used materials for both screen and spherical matrices. Some regenerator fabrication utilizes the techniques of bonding the regenerator material together for more simplified installation, maintaining the integrity of the material or containment of loose particles from system contamination. This research examines the effects of diffusion bonding stainless steel screen stacks and the manufacturing technique to epoxy bond lead spheres into a monolithic yet porous bed. The results of the experiments are compared with the previous data of comparable non-bonded materials.[2,3]

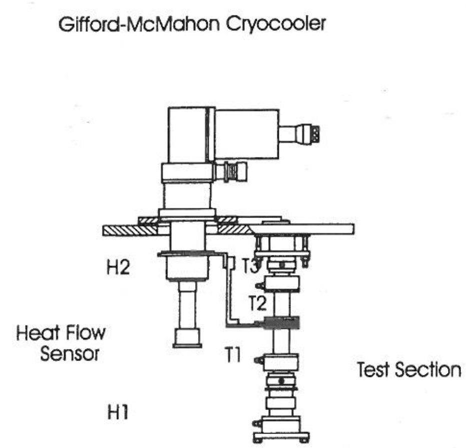

Figure 1. Experimental test apparatus.

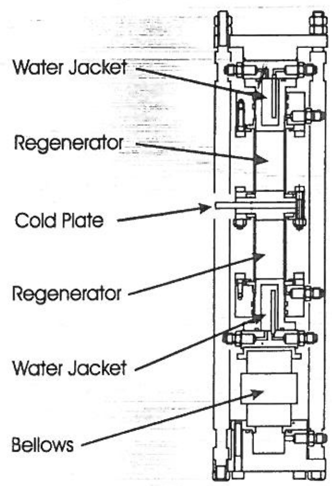

Figure 2. Experimental test section.

EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 shows the experimental apparatus used for the study. The apparatus consists mainly of a test section, a two-stage Gifford-McMahon (GM) cryocooler, a heat flow sensor, and a vacuum vessel (not shown in Fig. 1).

The details of the test section are shown in Fig. 2. Two identical regenerators are used in this apparatus. Regenerator cylinders are made of fiberglass-epoxy, with an inner diameter of 24.4 mm and a length of 55 mm. The wall thickness of each cylinder is 1 mm. Heat conduction along the length of the cylinder wall of a single regenerator from room temperature to 80 K is estimated to be 0.21 W from published thermal conductivity data.[4] Helium gas lines are connected to the regenerator to change the filling pressure in the regenerators. The pressure can be varied from vacuum to 2.0 MPa. Multi-layer insulation was wrapped around the test section to reduce radiation heat loss.

The cold ends of both regenerators are connected to a cold plate, which is cooled by the GM cryocooler by the heat flow sensor. The hot ends of both regenerators are capped by piston-shaped water jackets. Flowing water maintains the hot end temperature at room temperature. A bellows is attached to the lower water jacket. The cold plate and the two regenerators are free to move with respect to the water jackets, so the force exerted by the bellows is applied equally to both regenerator columns of bonded matrix materials.

The heat flow sensor is mounted between the cold plate and the first stage of the GM cryocooler. A flexible thermal link between the cold plate and the heat flow sensor allows for movement of the cold plate when the bellows pressure is changed. The heat flow sensor consists of a copper bar and two silicon diode thermometers. The copper bar is made of oxygen-free copper with a cross-sectional area of 72 mm^2 and a length of 135 mm. The distance between the two thermometers is 91.3 mm. The relationship between heat flow through the copper bar and temperature difference was calibrated before these experiments by using a heater attached to the cold end.

The experimental procedure is as follows. After pumping the vacuum vessel, the two-stage GM cryocooler is turned on. Both the cold plate and the heat flow sensor are cooled by the first stage of the GM cryocooler. The cold plate temperature is kept at a constant temperature by the temperature controller using a silicon diode thermometer at the cold plate and an electric heater mounted on the GM cryocooler first stage. The cold plate temperature can be varied over a wide temperature range but for these tests was maintained at 80 K. The temperature stability could be maintained to within ±0.05 K. Once the cold plate temperature is set

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REGENERATOR SAMPLES

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EXPERIMENTAL RESULTS A

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and the temperature difference at the heat flow sensor is measured, an additional heat load is supplied to a heater mounted on the cold plate, and its effect on the temperature difference at the copper bar is measured. The heat loads, the temperature differences, and the calibration curve obtained previously are used to calculate the heat flow through the heat flow sensor. The calculated heat flow here includes the heat conduction through both bonded matrix materials, the two fiber-glass-epoxy cylinders, and other heat losses, such as radiation loss and heat conduction loss through instrument wires. In a separate experimental run, the heat flow through the regenerators without any matrix material and with a vacuum inside was measured to provide information needed to determine the heat flow through the columns of matrix material only.

REGENERATOR SAMPLES

The materials used for the experiments were sintered stainless steel screens and epoxy bonded lead spheres. The 316L stainless steel screens were 325-mesh with 35.6μm (0.0014") wire diameter. The screens were cut into a square pattern and stacked to a specified height. The material was heated in a vacuum furnace to diffusion bond the contact points of the stainless steel. This procedure produces a block of stainless steel screen material. The diffusion bonded (sintered) block of screen was commercially fabricated. Our experience has shown that the diffusion bonding process takes place at a temperature of approximately 1100 °C. The stainless steel block was then machined using a wire electrical discharge machining (EDM) process. The cylinders were a sliding fit inside the G-10 cylinders used in the experimental apparatus. This sample was shorter than the existing G-10 cylinders so copper discs were made to fill the volume in the G-10 regenerator. Knowing the geometry as well as the mass of the sample allows us to calculate the porosity of the material, which for this sample was 0.6043. This porosity is lower than the standard value of 0.64 for 325-mesh screen. This lower porosity of the sintered screen is caused by the preparation and diffusion bonding procedure for the material.

The electrical resistivity of a similar sintered screen cylinder was measured and found to be 29.3 μΩ·m when the sample porosity is taken into account in the calculation of the cross-sectional area. When compared with solid stainless steel with a resistivity of 0.74 μΩ·m the ratio $\rho_{solid} / \rho_{sintered} = 0.025$ suggests that according to the Wiedeman-Franz Law the thermal conductivity degradation factor will be about 0.025 under vacuum conditions.

The epoxy coated lead spheres were cast into a thin-wall G-10 housing utilizing a cryogenic epoxy thinned with acetone.[4] The mass of epoxy remaining after being cured is only 0.11 % of the mass of the bonded spheres. The small amount of epoxy used has negligible influence on the gas flow characteristics of the regenerator. The spheres were made of 95% Pb + 5% Sb and had a diameter of 102 ± 13 μm. The cured sample is a monolithic regenerator material that provides a solid and porous test section for our experiments. Knowing the geometry and the mass of the material allowed us to calculate the porosity of the material, which was an average of 0.3881 for both regenerator sections. Characteristics of the epoxy packed bed regenerators with the G-10 housing are given in Table 1. The G-10 housings had a 0.25 mm wall thickness that fit precisely into the existing G-10 regenerators of the experimental test apparatus. The length of the G-10 housings matched the existing G-10 regenerator sections.

EXPERIMENTAL RESULTS AND DISCUSSION

The first measurement was of the heat leak through the G-10 regenerator cylinders without matrix material inside and under high vacuum conditions. The cold plate temperature was 80 K

Table 1. Characteristics of the epoxy-bonded lead sphere regenerators.

	Weight of packed bed with epoxy (g)	Porosity of packed bed with epoxy (%)	Est. Amount of epoxy in the regenerator (g)
Regenerator #1	141.632	38.92	0.164
Regenerator #2	142.095	38.69	0.154

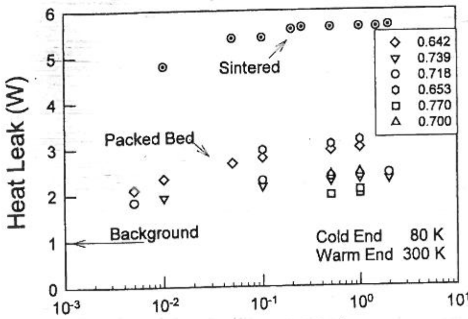

Figure 3. Stainless steel screen.

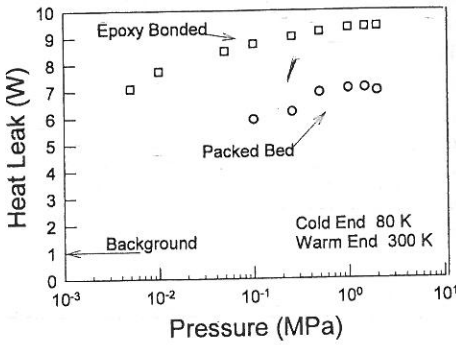

Figure 4. Lead spheres.

and the hot plate temperature was 285 K. The measured total heat leak was 1.06 W, with 0.42 W the calculated heat conduction through the cylinder wall of the two regenerators. These measurements gave a total background heat leak of the test apparatus and this value would be subtracted from all heat leak measurements for the materials tested.

The regenerator test matrices for each material were installed into the experimental test section and the heat leak was measured from vacuum condition up to a helium gas pressure of 2 MPa. The effects of the helium gas pressure over the operating pressure range can be seen in Figure 3 and Figure 4. The heat leak increases with the increasing helium pressure until there is little significant change for pressures above 0.5 MPa. This can be explained by the heat transfer mechanism in the regions of molecular flow, viscous flow and intermediate flow along with the pressure dependence of mean free path and thermal conductivity of helium gas. The heat leak rises in the molecular flow region where the heat transfer is proportional to gas pressure and levels out in the viscous flow region where the heat transfer is proportional to the thermal conductivity and is independent of pressure for an ideal gas. The effects of mean free path indicate that most of the heat is transferred by the helium gas in a region very close (~3μm) to the individual contacts between the wires or the spheres.

Figure 3 shows the heat leak values of the sintered 325-mesh stainless steel screen. These results are plotted with previous research done at NIST with standard 325-mesh stainless steel screens packed into the same G-10 regenerators and using the same test apparatus. The heat leak values of the screens were measured under various porosities over the same He pressure range. The data shows how the heat leak values of the sintered screens are approximately 2.5 times higher than that of the average value of the standard packed screens at 2 MPa. This higher heat leak is a result of the enhanced thermal contact at the diffusion-bonded metal-to-metal contacts as well as a result of the higher cross-sectional area of the metal due to a lower porosity. In addition the sintered screen samples were shorter than the packed screen samples. These differences in porosity and length will be factored out in the calculation of the thermal conductivity degradation factor.

Figure 4 shows the heat leak values of the epoxy bonded lead spheres. These data are plotted with previous data taken at NIST using standard packed beds of lead spheres utilizing the same experimental test section and apparatus. The data show that the heat leak value for the epoxy bonded spheres is approximately 1.35 times higher than the value for the standard packed sphere bed at 2 MPa. This heat leak increase can be contributed to the enhanced thermal contact of the boundaries due to the epoxy. The porosity values for the epoxy bonded lead spheres and the standard lead sphere packed bed were 0.3881 and 0.38 respectively.

Because of the geometry of the stainless steel screen and the lead sphere matrix, the thermal conduction is reduced compared to a solid bar of the same material and same cross-sectional area as the metal in the regenerator cylinder. Therefore to estimate this heat leak through the matrix columns, a conduction degradation factor f_c is applied. The actual conduction through the regenerator matrix is then given as:

$$\dot{Q} = f_c(A_t/L)(1-n_g)\int_{T_c}^{T_h} kdT, \tag{1}$$

where

$\dot{Q}$: Heat flow through matrix material
f_c: Conductivity degradation factor
A_t: Total cross-sectional area of matrix
L: Length of matrix
n_g: Porosity of material
T_c: Temperature at cold end of regenerator
T_h: Temperature at hot end of regenerator
k: Thermal conductivity of regenerator matrix material

In the calculations for these measurements the integrated values of thermal conductivity between 80 K and 290 K for the stainless steel and the 95% Pb + 5% Sb were 25.26 W/cm·K and 55.07 W/cm·K, respectively.[5,6]

Figure 5 and Figure 6 show how the conductivity degradation factor (f_c) varies with increasing pressure within the regenerator for the 325-mesh stainless steel screen and the packed bed lead sphere material of both the bonded matrix and the packed bed regenerators. This degradation factor begins to level out at a pressure of 0.5 MPa, which is explained by the effects of pressure relative to mean free path and thermal conductivity. The data show that the conductivity degradation factors for both of the bonded materials are higher than that of the non-bonded screen and sphere material. This is consistent with the heat leak data as shown previously. The conductivity degradation factor for the sintered stainless steel screens was 0.18, and for the epoxy bonded lead spheres the factor was 0.12 for pressures above 1 MPa. The data show that the comparison of the heat leak data to the conductivity degradation factor has a consistent difference between the lead sphere materials but that the comparison is quite different for the stainless steel material. This can be explained by the length differences of the matrix material and by the different porosity values. The lengths of the lead material were consistent and the porosities were about the same.

CONCLUSIONS

Measurements were performed to observe the thermal conduction properties of sintered stainless steel and epoxy bonded lead spheres and the results compared to measurements taken on stacked stainless steel screens and packed lead sphere beds. These bonding procedures are helpful for some regeneration construction and the effects of performing these bonding procedures would be helpful in evaluating loses associated with regenerator performance.

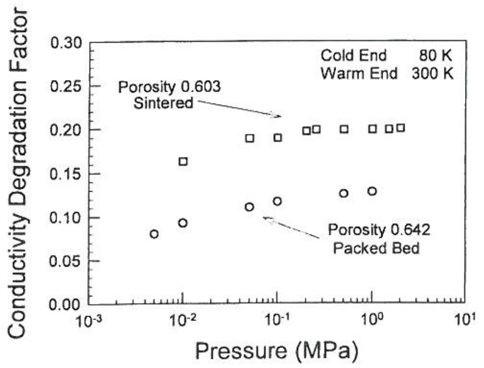

Figure 5. Stainless steel screen.

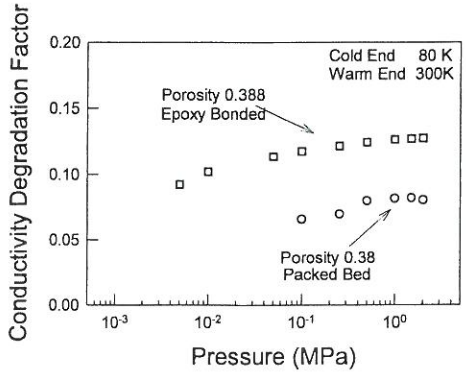

Figure 6. Lead spheres.

Measurements as a function of helium gas pressure indicate that most of the conduction between the individual wire or spheres is through the helium gas within a few microns on the contact point rather than directly through the contact. Bonding the layers by sintering or with thinned epoxy increases the conduction across the contact points, but that the conduction remains small compared with the conduction through the helium gas near the boundary. Thus, the increased conduction caused by epoxy bonding or sintering is small enough so as not to significantly degrade the performance of regenerative cryocoolers that use the bonded regenerators. The thermal conductivity degradation factors presented here for the bonded regenerators allow their geometry to be optimized by using REGEN3.2 or other design software.

ACKNOWLEDGMENT

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REFERENCES

1. Walker, G., *Cryocoolers*, Plenum Press, New York (1983).
2. Lewis, M.A., Kuriyama, T., Kuriyama, F., and Radebaugh, R., "Measurement of Heat Conduction Through Stacked Screens," *Advances in Cryogenic Engineering*, Vol. 43, Plenum Press, New York (1998), pp. 1611-1618.
3. Lewis, M.A., and Radebaugh, R., "Measurement of Heat Conduction Through Metal Spheres," *Cryocoolers 11*, Kluwer/Plenum Publishers, New York (2001), pp. 419-425.
4. Mérida, W.R., and Barclay, J.A., "Monolithic Refrigerator Technology for Low Temperature (4K) Gifford-McMahon Cryocoolers," *Advances in Cryogenic Engineering*, Vol. 43, Plenum Press, New York (1998), pp. 1597-1604.
5. Radebaugh, R., Gary, J., Marquardt, E., Louie, B., Daney, D., Arp, V., and Linenberger, D., *Measurement and Calculation of Regenerator Ineffectiveness for Temperatures of 5 to 40 K*, Flight Dynamics Directorate, Wright Laboratory, March, 1992.
6. Childs, G.E., Ericks, L.J., and Powell, R.L., *Thermal Conductivity of Solids at Room Temperature and Below*, U.S. Department of Commerce, NBS Monogram 131.

Regenerator Lo
Temperatures a

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ABSTRACT

We report the design o
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INTRODUCTION

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