Measurement of Heat Conduction through Metal Spheres

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ABSTRACT

This paper describes the results of the measurements of heat conduction through a bed of packed metal spheres. Spheres were packed in a fiberglass-epoxy cylinder, 24.4 mm in diameter and 55 mm in length. The cold end of the packed bed was cooled by a Gifford-McMahon (GM) cryocooler to cryogenic temperatures, while the hot end was maintained at room temperature. Heat conduction through the spheres was determined from the temperature gradient in a calibrated heat flow sensor mounted between the cold end of the packed bed and the GM cryocooler. The samples used for these experiments consisted of stainless steel spheres, lead spheres, and copper spheres. The spheres were screened to obtain a uniform diameter of 80 to 120 μm. Porosities of the packed beds varied between 0.371 and 0.398. The measurements to determine the thermal conductance were carried out with various pressures of helium gas in the void space. The results indicated, as expected, that the helium gas between each sphere enhances the heat conduction across the contacts between the individual spheres by several orders of magnitude compared with vacuum in the void space. The conduction degradation factor, defined as the ratio of actual heat conduction to the heat conduction if the metal were in the form of a solid rod of the same metal cross-sectional area, was about 0.11 for stainless steel, 0.08 for lead, and 0.02 for copper. The conduction degradation factor of 0.11 for stainless steel spheres agrees very well with the factor of 0.10 for stainless steel screen measured previously in the same apparatus.

INTRODUCTION

Beds of packed spheres are commonly used as a regenerator for cryocoolers operating at temperatures below about 80 K.[1] Because of the large temperature gradient in the regenerator, heat conduction through the packed spheres can be a significant loss. Previous studies of heat flow through columns of packed spherical material have considered conduction in the fluid due to a temperature gradient, conduction within solid particles, conduction from one particle to the next through a separating film, heat transfer between particle and main body of the fluid, enthalpy carried along by the moving fluid, and possible heat generation through a chemical reaction.[2] However, in cryocooler regenerators, the high thermal conductivity of the helium working fluid can transport a large fraction of the heat between the solid contacts.[3] Schumann and Voss investigated experimentally the thermal conductivity of packed beds in static gas.[4] Recent work by Slavin et al.[5] considers the thermal conduction in packed beds of alumina spheres in static helium gas, but the temperature range is 100 to 500 degrees Celsius. Experimental and analytical research data for heat

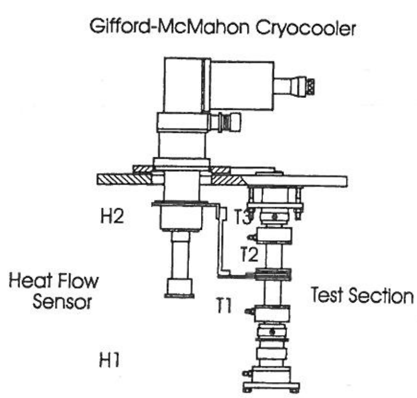

Figure 1. Experimental test apparatus.

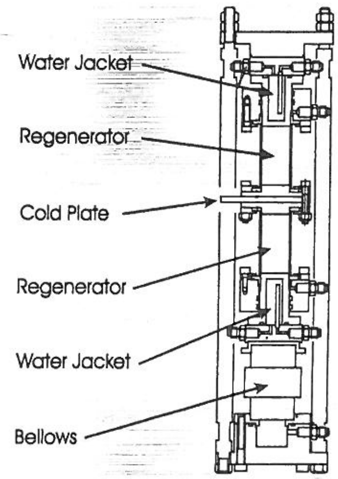

Figure 2. Experimental test section.

conduction loss are not available for practical use in the design of cryocooler regenerators. The purpose of this study is to directly measure the heat conduction loss from room temperature to cryogenic temperatures through packed spheres in static helium gas.

EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 shows the experimental apparatus used for the present 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 and were described previously.[3] 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.[6] Stainless steel, copper, and lead spheres were used in the study. The sphere materials were carefully screened to obtain diameters between 80 and 110 μm. The spheres were packed in the regenerator cylinder to a height of approximately 45 mm. 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 were connected to a cold plate, which was cooled by the GM cryocooler with the heat flow sensor between them. The hot ends of both regenerators were capped by piston-shaped water jackets. Flowing water maintained the hot end temperature at room temperature. A bellows was attached to the lower water jacket. Changing the filling pressure of the helium in the bellows moves the lower water-cooled piston to apply any desired load. For these measurements, an applied load of 5.1 MPa on the packed sphere bed was used. The cold plate and the two regenerators were free to move with respect to the water jackets, so the force exerted by the bellows was applied equally to the two regenerator columns of packed spheres.

The heat flow sensor was 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.

Table 1. Characteristics of thermal conduction spheres

Material	Stainless Steel 304	Lead Pb + 5% Sb	Copper 99.9%
Sphere Diameter(μm)	80 to 120	80 to 120	80 to 120
Mean Density (g/cm^3)	7.8	11.107	8.9
Porosity of Sphere Bed	0.371	0.380	0.398

The experimental procedure was as follows. After pumping the vacuum vessel, the two-stage GM cryocooler was turned on. Both the cold plate and the heat flow sensor were cooled by the first stage of the GM cryocooler. The cold plate temperature was 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 could be varied over a wide temperature range, but for these tests was maintained at 80 ±0.05 K. Once the cold plate temperature was set and the temperature difference at the heat flow sensor was measured, an additional heat load was supplied to a heater mounted on the cold plate, and its effect on the temperature difference at the copper bar was 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 sphere beds, the two fiberglass-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 packed spheres was measured to provide information needed to determine the heat flow through the columns of sphere beds only.

Characteristics of the spheres tested in this study are given in Table 1. The porosity for each type sphere shown in this table is calculated using the density of the material and the actual mass of spherical material used to fill each regenerator column volume to capacity. To achieve the desired results, the regenerators along with material to be tested had to be assembled to minimize the amount of void space that was inherent to the G-10 cylinders and sphere material. The test sections needed to be packed efficiently to obtain low porosity values. The spherical material was poured into the regenerators and placed on a vibration apparatus that allowed the spheres to tightly pack together in a uniform distribution. As the material settled over the desired vibration time, the regenerators were filled to maximum capacity. This enabled us to reduce the void volumes in the G-10 cylinders as much as possible. Once the regenerators were packed to the necessary uniform and solid packing, the G-10 regenerators were installed into the apparatus. Using this procedure, we were able to obtain porosity values that were near the theoretical value expected for packed beds of spheres for a known volume and a specific material density.

EXPERIMENTAL RESULTS AND DISCUSSION

The first measurement was performed to determine the system heat leak through the two regenerators without any spherical material packed inside and with vacuum pressure applied to the regenerator tubes. The cold plate temperature was 80 K and the hot plate temperature was 285 K. The total measured heat leak was 1.06 W, with 0.42 W calculated to be the heat conduction through the cylinder walls of the two regenerators. The 1.06 W of heat flow was then subtracted from subsequent measurements with spheres in the regenerators and various helium pressures applied to obtain the heat conduction through the packed sphere beds.

The effect of helium gas pressure inside the regenerator on the total measured heat leak is shown in Figure 3. These measurements were made with the cold end of the apparatus maintained at a constant temperature of 80 K. As this figure shows, the heat leak increases rapidly with increasing helium pressure until there is little significant change for pressures above 0.5 MPa. Figure 4 shows the pressure dependence of the mean free path and thermal conductivity of bulk helium gas at 80 K, 200 K, and 300 K. Although the thermal conductivity of bulk helium at pressures to 5 MPa is almost independent of pressure, the heat leak varies with pressure conditions at pressures

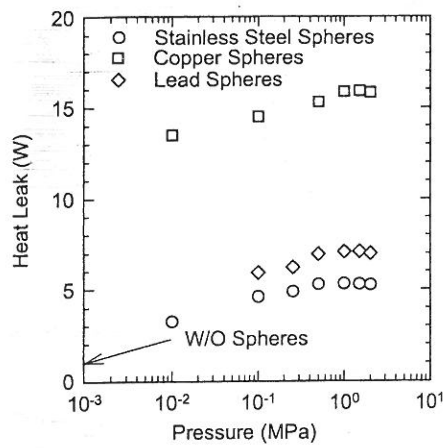

Figure 3. Heat leak vs. helium gas pressure.

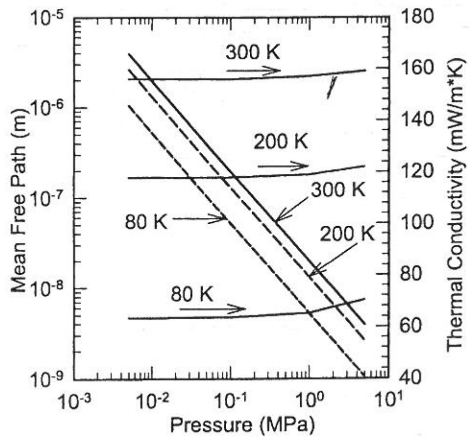

Figure 4. Mean free path and thermal conductivity vs. pressure dependency over temperature ranges.

below 0.5 MPa. In order to understand the test results, we discuss the heat transfer mechanism in the regions of molecular flow, viscous flow, and intermediate flow. Generally gas flow can be treated as molecular flow when the mean free path, ℓ, is larger than 10 times the distance, *d*, between the two solid plates which transfer the heat. On the other hand, when ℓ is less than 0.01 *d*, the gas flow can be treated as viscous flow. In the viscous flow region, heat transfer between two solid plates is proportional to the thermal conductivity and is independent of pressure for an ideal gas. In the molecular flow region, the heat transfer is proportional to the gas pressure. Figure 3 shows that at approximately 0.5 MPa the thermal conduction through the helium gas has reached the viscous flow region where the mean free path of the helium atoms has become less than 0.01 *d*. Because the temperature varies from 80 to 285 K along the length of the regenerator, the mean free path of helium at 0.5 MPa according to Figure 4 varies from 0.010 to 0.039 μm. Therefore, the effective distance between each spherical ball contributing most to the heat flow is about 1 to 4 μm, or 100 times the mean free path. Since the sphere is in the range of 80 to 110 μm, most of the heat is transported by the helium gas in a region very close to the individual contacts between spheres. According to Fig. 3, the heat leak at very low helium gas pressure approaches a value very near the background value. Such behavior indicates that there is very little electronic heat conduction associated with direct metallic contact between the spheres, in agreement with electrical resistance measurements.[7] The electrical resistance measurements[7] indicate a heat conduction of about 4 mW for our system.

Because of the many spheres in a packed bed, the thermal conduction through the bed is reduced compared to a solid bar of the same material and same cross-sectional area as the metal in the sphere bed. Therefore, to estimate this heat leak through the packed spherical columns, a conduction degradation factor f_c is applied. The actual conduction through a packed sphere bed is then given as a proportional reduction to the bulk material conduction as

$$\dot{Q}_c = f_c(A_t / L)(1 - n_g)\int_{T_c}^{T_h} k dT, \qquad (1)$$

where

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

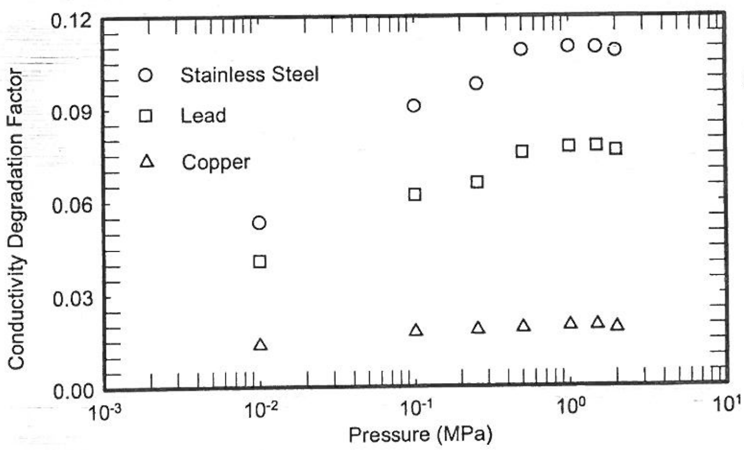

Figure 5. Pressure (MPa) vs. CDF for packed bed spheres.

Figure 5 shows how the conductivity degradation factor (CDF) varies with increasing pressure within the regenerator for the stainless steel, lead, and copper sphere material. This value begins to level out at around a pressure of 0.5 MPa, which is consistent with the previous explanation of mean free path and thermal conductivity. The values of 0.11, 0.077, and 0.019 for the degradation factors of stainless steel, lead, and copper material, respectively, represent our data well over the pressure range above 0.5 MPa at a temperature of 80 K. Earlier experiments[3] were performed in this test apparatus using various screen materials as the regenerator matrix. Figure 6 shows the conductivity degradation factor for stainless steel 400-mesh, 25.4 μm wire; 325-mesh 27.9 μm wire; and 325-mesh, 22.9 μm wire over a wide porosity range. These porosities were obtained using a static load of 5.1 MPa in addition to no load conditions. These data indicate that a value of 0.11 is a good representation of the conductivity degradation factor for the stainless steel screen material and agrees with the value of 0.11 in the present investigation for stainless steel spheres.

Our previous measurements[3] of phosphor bronze screen gave a degradation factor of about 0.025 compared with the value of 0.02 for the copper spheres. The slightly lower value for copper is consistent with a lower f_c for higher conductivity material. Table 2 gives the effective thermal conductivity integration between 80 and 300 K of various sphere and screen materials using Equation 1. Shown for comparison is the thermal conductivity of bulk helium gas.

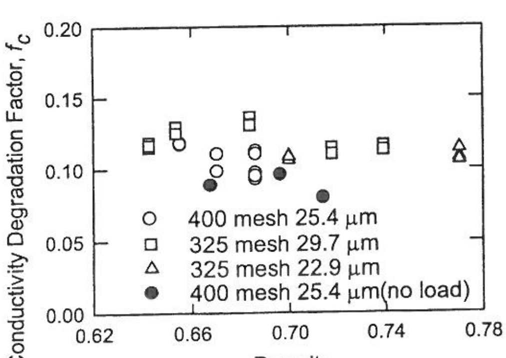

Figure 6. Porosity vs. CDF for stainless steel screens.

Table 2. Integrated Thermal Conductivity Values

Material	$\int_{T_c}^{T_h} kdT$ (W/cm)	f_c	$f_c \int_{T_c}^{T_h} kdT$ (W/cm)
Stainless Steel screen	27.83[6]	.110	3.06
Phosphor Bronze screen	151.29[8]	.022	3.33
Stainless Steel sphere	27.83[6]	.110	3.06
Lead sphere	57.95[9]	.077	4.46
Copper sphere	361.61[8]	.021	7.59

CONCLUSIONS

The heat conduction through packed spheres from room temperature to cryogenic temperature was measured experimentally. The experimental apparatus allows for a change in the regenerator material, the cold end temperature, and the helium gas pressure in the regenerator. The measurements were performed using stainless steel, lead, and copper spheres between 80 and 120 µm in size with a porosity of about 0.38.

The experimental results showed that the helium gas between each sphere contact point plays an important role in transporting the heat. The heat conduction through the packed beds was enhanced by at least two orders of magnitude using helium gas compared to vacuum conditions inside the regenerator. The heat conduction reached a constant maximum value for helium pressures above 0.5 MPa. A short helium mean free path of 0.010 to 0.039 µm, indicates that most of the heat is transported a distance of the order of 3 µm from one sphere to the next.

The conduction degradation factor, which is the ratio of actual heat conduction to the heat conduction where the regenerator material is assumed to be bulk, was about 0.11 for the stainless steel sphere materials, 0.077 for the lead sphere material, and 0.021 for the copper sphere material. This factor was relatively constant for the 80 K temperature at the cold end and for pressures over 0.5 MPa. For stainless steel and lead spheres the drop off below 0.5 MPa was much more significant than the copper spheres. This more constant value for the conductivity degradation factor for copper spheres could be attributed to possible deformation due to pressure applied during the experiments as well as a better heat transfer at the contacts

This test apparatus provided NIST with valuable information using the packed sphere columns as well as the stacked screens. The conductivity degradation factors that were obtained for the stainless steel materials of 0.11 were very consistent for both screen and spheres. These new conductivity degradation factors for calculating the thermal conduction through packed sphere columns gives valuable information for regenerator optimization. With the NIST regenerator optimization software REGEN3.1,[10,11] an improved coefficient of performance for regenerators can be achieved with proper optimization of regenerator geometry.

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