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EXPERIMENTAL RESULTS ON A LOW-TEMPERATURE MAGNETIC REFRIGERATOR

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ABSTRACT

A Carnot-cycle magnetic refrigerator has been designed, built, and tested in the temperature range of ~ 4 K to ~ 15 K. Gadolinium gallium garnet in the rim of a wheel is the refrigerant. The wheel rim rotates through a gap between two superconducting Helmholtz coils that produce a magnetic field of up to 6 T. Helium gas is used as the heat-transfer fluid in the hot and cold regions of the wheel. The refrigerator performance has been measured in an open-cycle flow system because no suitable low-temperature helium gas pumps were available for closed loop circulation of helium gas. Over one watt of cooling power with a temperature span of several degrees was achieved. At low frequencies the cooling power and temperature changes of the refrigerator match the entropy-temperature data used in the design. Problems associated with friction and gas mixing limit the performance at frequencies above about 0.1 Hz. Separate friction measurements suggest that gas flow control is the dominant problem that needs to be solved before significant improvement in refrigerator operation can be expected. The present measured efficiency is about 20% of Carnot if the drive motor efficiency is ignored. With friction and other losses in the drive motor mechanism, the overall efficiency is $\sim 1\%$ of Carnot.

INTRODUCTION

There are a growing number of commercial applications of superconducting devices that require refrigeration near liquid helium temperatures.¹ Open cycle helium systems may prove to be too expensive for long-term use on many of the larger scale superconducting devices. For applications with closed-cycle helium systems, there are several manufacturers of gas-cycle refrigerators that reach 10-to-20 K with a regenerative or recuperative cycle and then reach ~ 4 K with a Joule-Thomson (J-T) expansion loop.² Low efficiency and limited reliability of the J-T loop have led to several experimental programs around the world on magnetic refrigerators aimed at making a refrigerator stage which has higher efficiency and improved reliability over a J-T stage.³

This paper presents the results on a magnetic refrigerator operating in the 4-to-15 K temperature range under development at Los Alamos National Laboratory.

DESIGN SUMMARY

A rotational (wheel) design operating on a Carnot cycle between about 4 K and 15 K was selected for a magnetic refrigerator prototype because:

- the magnetic forces are almost balanced;
- continuous refrigeration is possible;
- a suitable characterized magnetic material was available; and
- the device could be the bottom stage of other refrigerators operating at higher temperatures.

Table I summarizes the design parameters of the magnetic refrigerator. A schematic of the refrigerator is shown in Fig. 1.

The wheel rim compartments (partially shown in Fig. 1) are filled with 178 g of roughly spherical particles of gadolinium gallium garnet (GGG) with a diameter of about 0.5 mm. The wheel is made from stainless steel with 100-mesh stainless steel screen on the inner and outer radius of the rim. The wheel rotates inside a stationary stainless steel housing that has two ducts installed on it (as shown in Fig. 2) to permit helium gas to flow radially through three of the GGG-filled compartments at each duct. One duct is located at a position where the GGG reaches 15 K as it is magnetized, and the other is located where the GGG reaches about 4.5 K as it is demagnetized. Two pumps will eventually be used to circulate helium gas through the wheel and two external heat exchangers: one for heat rejection and one to cool a thermal load. Also, the wheel can be rotated inside the housing by a drive motor outside the dewar via a magnetic coupling to avoid cold seals on a rotating shaft. The configuration in Fig. 1 illustrates the device as used for test purposes because no suitable helium gas pumps were available at the time of the tests.

TABLE I
CARNOT-CYCLE WHEEL DESIGN PARAMETERS

Cooling power - 0.66 W
Material - gadolinium gallium garnet (GGG)
Magnetic field - 6 T
Sink temperature - 15 K
Source temperature - 4.3 K
Magnetic Entropy Change - $3 \times 10^4 \text{ J/m}^3\text{K}$
O.D. of wheel rim - 13.9 cm
I.D. of wheel rim - 11.9 cm
Axial length of rim - 1.35 cm
Number of compartments - 36
Porosity - 50%
Operating frequency - 0.2 Hz
Helium gas pressure - 0.1 MPa

Figure 1. A schematic diagram of the 4-to-15 K magnetic refrigerator as it was operated in the test mode.

Figure 2. A top-view of the 4-15 K magnetic wheel and its housing that shows the ducts for the cold and hot helium gas flow regions.

The magnet consists of a pair of superconducting solenoids wound on soft iron cores and supported by a soft iron yoke for a magnetic flux return path and to support the two solenoids. The resultant c-shaped magnet was designed for a maximum field of 6 T in the gap of 2.2 cm between the two solenoids. The coils were wound with NbTi multifila-

nentary Formvar-insulated 0.081-cm diameter wire having a short-sample critical current of 353 A at 7 T. The coils were potted with Stycast 2850 FT epoxy as they were wound on the coil form. The calculated field profiles give a value of 1.47 as the ratio of the maximum field in the center of the coils to the minimum field in the gap, which illustrates one of the disadvantages of this magnet configuration. The soft iron used for the flux return path has a 7.62-cm X 7.62-cm cross section. The power leads are removable so that after the magnet is charged and put in persistent mode, the power supply can be turned down and the leads removed. The magnet is kept at ~4.2 K by filling the magnet container with liquid helium. Because the whole magnetic refrigerator operates in a vacuum chamber, the magnet container is single-walled and does not have any superinsulation directly on it. The sink temperature is limited to 15 K by the additional entropy from the entrained fluid and the stainless steel wheel components that rotate with the GGC. The housing reaches a steady-state temperature distribution and only indirectly affects the wheel by thermal conduction from 15 K to 4 K and by friction between the close-fitting wheel and housing. The data used for design calculation of the heat transfer, pressure drop, and longitudinal conduction are among the more conservative values published. The results of performance calculations for the wheel are summarized in Table II. The total work was calculated assuming a motor efficiency of 90% and a pump efficiency of 50%. The overall design efficiency obtained was 65% for the wheel rotating at 0.2 Hz, cooling a load of 0.66 W at 4.3 K and rejecting heat at 15 K. This efficiency is greater than that of a well-designed J-T loop.

However, one major problem that remains unsolved in this design is the entrained fluid (the helium gas) that rotates around with the GGC. The entrained fluid reduces the cooling power by acting as an internal thermal load and transfers helium from the cold section of the wheel to the hot section and vice versa thereby causing mixing of the two gases.

TABLE II
CALCULATED WORK RATES FROM VARIOUS MECHANISMS FOR A
CARNOT-CYCLE WHEEL REFRIGERATOR

<u>Item</u>		<u>$\dot{W}$ (Watts)</u>
$\dot{W}$	reversible	1.64
$\dot{W}_H$	conduction	0.046
$\dot{W}_H$	heat transfer	0.012
$\dot{W}_H$	pressure drop	0.011
$\dot{W}_c$	conduction	0.016
$\dot{W}_c$	heat transfer	0.012
$\dot{W}_c$	pressure drop	0.0001
$\dot{W}$	4-15 K conduction	0.18
$\dot{W}$	friction	0.10
$\dot{W}$	parasitic heat leak	0.10
$\dot{W}_H$	heat exchanger	0.060
$\dot{W}_c$	heat exchanger	0.060

EXPERIMENTAL RESULTS AND DISCUSSION

Tests on the magnetic refrigerator were performed in magnetic fields of 4 T and 5.6 T with variable frequency, helium gas flow rates, pressure, and helium gas temperatures at the inlets to the hot and cold ducts. The refrigerator was operated in an open cycle mode using helium gas from a dewar of liquid helium. Cryogenic valves on the inlets to both ducts allowed control of the mass flow through each of the ducts. The temperature of the inlet helium gas could be regulated separately for the hot and cold ducts by heaters in the paths of the incoming gas. The gas temperatures were measured using carbon-glass resistors at four locations in each duct and the flow rates were measured using Hastings mass flow meters.

The input power to the drive motor was measured for various conditions in the wheel (pressurized, evacuated, cooled to 75 K, etc.). The efficiency of the motor was also experimentally determined in a separate experiment.

A typical test sequence involved:

- (1) cool down of the system to the desired operating conditions;
- (2) fill the magnet container with LHe;
- (3) charge the magnet to give the desired field in the gap;
- (4) put the magnet in the persistent mode;
- (5) start rotation of the wheel;
- (6) record the operating data; and
- (7) stop the wheel rotation and/or change the operating conditions.

Using this procedure, the cooling power was determined: 1) as a function of wheel rotational speed; 2) as a function of the cold temperature; and 3) as a function of the temperature span between the cold temperature and the hot temperature.

Cooling power as a function of the cold temperature

The net cooling load, $\dot{Q}_C$, as a function of the average temperature span, T_A , for 4 T and 5.6 T at 0.08 Hz with $\bar{T}_C = 5.5$ K is shown in Fig. 3. The net cooling load is determined by the mass flow rate, $\dot{m}$, and the temperature decrease of the helium gas, ΔT_C , as it flows through the OGC (i.e., $\dot{Q}_C = \dot{m} C_p \Delta T_C$) where C_p is the heat capacity of the helium gas. The average temperature span is the average gas temperature across the wheel at the hot duct, $\bar{T}_H$, minus the average gas temperature across the wheel at the cold duct, $\bar{T}_C$, (i.e., $T_A = \bar{T}_H - \bar{T}_C$). The total refrigeration capacity of the prototype is the net cooling load plus other loads such as friction. The heat rejected at the hot duct of the wheel can be measured in a similar way which allows the work rate (and efficiency) to be calculated and compared with the input power to the drive motors.

The net cooling load as a function of two different temperature conditions is shown in Fig. 4. In one condition, the average helium gas temperature across the cold inlet and outlet ducts is held constant at about 5.5 K and the average helium gas temperature across the hot inlet and outlet ducts is gradually raised from about 9 to 13 K. The results from this experiment are shown in the left side of Fig. 4. In the other condition, the average temperature across the hot inlet and outlet ducts is held constant at about 22.5 K while the average helium gas temperature across the cold inlet and outlet ducts is gradually decreased from about 20.5 to 19 K. The results from these two experiments were mapped onto the total entropy-temperature diagram for the OGC and stainless steel wheel components as shown in Fig. 5. The temperature and entropy

changes, at B → C for example, give an indication of the potential cooling capacity. The experimental entropy changes and temperatures shown compare well with those expected from the design data of Fig. 5. For example, the data on the right side of Fig. 4 indicate a minimum

Figure 3. A plot of cooling power as a function of the average temperature span of the 4-to-15 K magnetic refrigerator at two different field strengths.

Figure 4. A plot of cooling load vs. operating temperature for two different gas-temperature conditions with constant gas mass flow rate at 4 T and 0.08 Hz.

Figure 5. The total entropy of the magnetic material plus wheel components as a function of temperature. Several experiments are illustrated on these curves and are explained in the text.

temperature of about 18.5 K with zero cooling power and the curves in Fig. 5 show that demagnetizing GGG from 4 T and 22.5 K should produce about 18.5 K! Similar conclusions from the other data indicate that at 4 T and 0.08 Hz, the refrigerator is operating as expected from the S-T design data.

Cooling power as a function of rotational speed

A curve of the cooling power as a function of the rotational speed of the wheel for a 4 T field and fixed helium flow rates is shown in Fig. 6. The cooling power increased almost linearly (as expected) with rotational speed at low frequencies but peaked at about 0.1 Hz, and dropped rapidly to zero by 0.2 Hz. The calculated frequency dependence of the cooling power is a much broader curve with a peak at about 0.2 - 0.5 Hz with significant cooling power still at 1 Hz (although the efficiency has decreased substantially). These data indicate that something such as friction, internal mixing, entrained fluid, flow between hot and cold ducts, etc., is much larger than anticipated and is limiting the cooling capacity of the refrigerator.

Frictional power

In order to determine the contribution of frictional heating to the cooling power as a function of frequency, a series of tests were conducted. The wheel was cooled to about 6 K and then, under different pressures of helium gas and no magnetic field, was rotated at various speeds, while the temperature increase of the stationary housing and gas ducts was measured. Data were taken at 0, 0.033, 0.051, 0.081, 0.098, 0.132, and 0.153 Hz. From these heating curves the frictional heat generated as a function of frequency was estimated. The results are shown in Fig. 7. These results show that the frictional heating increases less than linearly and probably indicates the errors due to conduction heat leak from the housing and other limitations of these

friction experiments. Nevertheless, the general magnitude of the heating from friction is probably close to these values. If this assumption is true, the frictional heating reduces the cooling power by 10-15%. This percentage reduction should remain approximately constant in the range of interest because both the friction and cooling power are linearly proportional to frequency.

Figure 6 The net cooling power of the 4-to-15 K magnetic refrigerator as a function of wheel rotation rate at an applied magnetic field of 4 T and a fixed $\bar{T}_C$ and $\bar{T}_H$.

Fig. 7 The frictional heating rate as a function of wheel rotation rate for the 4-to-15 K refrigerator in zero applied field with the housing at less than 1×10^{-3} mm pressure of helium gas.

Efficiency

The efficiency was determined in two ways for the refrigerator at 4 T and 0.08 Hz. The first estimate was obtained from the measured values of Q_H and Q_C . The difference is W which immediately gives the efficiency, η , according to

$$\eta = \frac{Q_C}{W} \left(\frac{T_H}{T_C} - 1 \right)$$

This method gives ~20% of ideal Carnot efficiency for the refrigerator. The second method is to measure the total input power to the drive motor and the measured value of Q_C . Inserting these values into the above equation gives ~1% of Carnot efficiency. This latter value includes all of the motor and drive inefficiencies. We independently measured the drive motor system efficiency as only 5-6% of ideal so the two measurements above are consistent.

SUMMARY AND CONCLUSIONS

The initial tests of this 4-15 K prototype are very encouraging. The efficiency of the refrigerator itself is about 20% of Carnot efficiency in 4 T field. Presumably, the efficiency will increase at higher fields. There are many reasons why the efficiency is only ~20% of ideal in the initial runs. For instance, typical temperature differences between the inlet and outlet helium gas streams are ~1.5 K and ~4 K at the cold and hot ducts, respectively. Given a hot temperature of ~10 K and cold temperature of ~6 K, the extra temperature span reduces the maximum expected efficiency to ~33% of ideal.³ In the design calculations, a temperature change of ~0.3 K was used. By proper adjustment of the helium mass flow rate the temperature spans can be reduced and the efficiency increased.

The dramatic reduction in cooling power about 0.1 Hz is most likely due to hot gas mixing with cold gas. Direct leakage from the hot to cold duct and entrained gas in the porous GCG are two mechanisms for gas movement. The clearance seals of several thousands of an inch that are used in this device may be insufficient to contain the gas in the appropriate regions. In order to determine which of these two mechanisms is the dominant problem, experiments are planned to determine the cooling power as a function of frequency for different static helium gas pressures in the housing. These experiments will be done when a good low-temperature gas pump is found or developed so the refrigerator can be operated in a close-cycle mode.

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