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DESIGN AND CONSTRUCTION OF A STATIC MAGNETIC REFRIGERATOR OPERATING BETWEEN 1.8 K AND 4.5 K

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Following pioneer work a decade ago at CEA/CEN-Grenoble, France we have designed and constructed a static magnetic refrigerator with a capacity of about 20 W, operating on a quasi-Carnot cycle between 1.8 and 4.5 K. The active core, which contains 10.1 kg of single-crystal gadolinium-gallium garnet (GGG), is magnetized and demagnetized by a 3.5 T pulsed-field, low-loss superconducting magnet operating at 4.5 K. Thermal switching to the cold and warm sources is produced by alternatively flushing the core with liquid helium from the 1.8 and 4.5 K baths, by means of alumina-piston and -cylinder displacer pumps. Precise modelling of thermodynamic properties of GGG, as well as detailed analysis of the different sources of irreversibility, allow to estimate the available refrigeration power and optimize the operating cycle.

DESIGN

A schematic diagram of the static magnetic refrigerator is shown in Figure 1. The refrigerator is operating on a quasi-Carnot cycle between the bath temperatures of 1.8 and 4.5 K at a constant pressure of 1.3 bar. The pulsed magnet consisting of the superconducting coil and the iron yoke is immersed in liquid helium at 4.5 K. The active core made of single-crystal gadolinium-gallium garnet (GGG) is magnetized and demagnetized by the low-loss superconducting magnet between 0 and 3.5 T corresponding to a pulsed current of 0 to 400 A supplied through vapour-cooled current leads. Magnet design and measurements are documented in detail in [1]. Mechanically actuated valves are built in to allow the thermal isolation of the core during the adiabatic phases. Alumina-piston and -cylinder displacer pumps are used to flush the core alternatively from the two baths, realizing the isothermal phases of the Carnot cycle. Figure 2 shows a view of the magnetic refrigerator upon assembly.

A magnetization cycle consists of two adiabatic and two isothermal phases: the magnetic refrigerant is steadily magnetized with closed valves starting at 1.8 K until the core temperature of 4.5 K is reached (adiabatic magnetization). At this temperature the valves AA' are opened and the core is flushed by helium from the warm bath, thus releasing heat to the 4.5 K level (isothermal magnetization). When the field of 3.5 T is reached the valves are closed again and the field is steadily decreased until the core reaches the temperature of the cold bath (adiabatic demagnetization). The valves BB' are opened and the core is flushed by helium from the cold bath, thus absorbing heat at 1.8 K (isothermal demagnetization).

MATHEMATICAL MODELLING OF THE ENTROPY OF GGG

The thermodynamic analysis of the refrigeration cycle requires a correct description of the entropy of GGG in the domain of temperature and magnetic field of interest [2]. The entropy of magnetic materials is described by

$$s(T, H) = s_0 + \int_{T_0}^T \frac{c_{H=0}(T)}{T} dT + \int_0^{\mu_0 H} v \left[\left(\frac{\partial M}{\partial T} \right)_H \right] d(\mu_0 H)$$

where the first term represents the reference entropy, the second term the entropy at zero field depending on temperature, the third term the entropy due to magnetization of the material. A function for the specific heat at zero field $c_{H=0}$ depending on temperature T was found by a fit to measurements taken from reference [3]. The fit is accurate within 0.2 % in the temperature range from 1 to 4 K. The

magnetization function of GGG depending on temperature and applied field was empirically formulated [4]. The entropy as a function of induction was calculated for different temperatures and is shown in Figure 3 where the reference entropy is set to 0 for $T_0=1$ K, $H=0$. The entropy variation becomes smaller with increasing temperature. In the temperature range from 1.8 to 4.5 K, the entropy variation with the magnetic induction is large, showing the interest of using GGG as working refrigerant in this domain.

SIMULATION OF THE MAGNETIC CARNOT CYCLE

The simulation of the refrigeration cycle analyses the effect of the different irreversibilities on cooling power and efficiency compared to an ideal cycle. Inherent irreversibilities are the trapping of helium inside the core cooling channels during the adiabatic phases, the heat transfer resistance between the helium and the core, the pressure drop of helium during the isothermal phases and the inhomogeneous field produced by the magnet.

The following assumptions were made for the simulation:

- Helium and core have the same temperature during the adiabatic phases.
- No temperature gradient is established inside the core due to the inhomogeneous field because of the high heat conductivity. An average temperature is established.
- The heat transfer coefficients for the isothermal magnetization and demagnetization are respectively $0.67 \text{ Wcm}^{-2}\text{K}^{-1}$ (nucleate boiling) and $0.23 \text{ Wcm}^{-2}\text{K}^{-1}$ (Kapitza conductance). Taking into account these coefficients for the calculation of the minimum duration required for the heat exchange between core and helium leads to Δt_w of 0.27 s for the isothermal magnetization and Δt_c of 0.34 s for the isothermal demagnetization.

The efficiency is defined by the ratio of refrigeration energy to rejected heat. For an ideal Carnot cycle using the entropy model developed, the calculated efficiency is 0.39 and a refrigeration energy of 145 J is produced by the 10.1 kg GGG-core. Table 1 summarizes the cumulative influence of the irreversibilities on refrigeration energy E_{cool} and efficiency η_{cycle} .

Table 1 Cumulative influence of the irreversibilities on refrigeration energy and efficiency ($\Delta t_w = 0.27$ s, $\Delta t_c = 0.34$ s)

	Ideal Carnot	+ Inhomogeneous field	+ Trapped helium	+ Heat transfer resistance
η_{cycle}	0.39	0.39	0.34	0.30
E_{cool} [J]	145	134	53	49

Taking into account the inhomogeneous field inside the core volume calculated using the core-magnet geometry and the material properties, yields the same efficiency as the ideal cycle and a reduction in refrigeration capacity of 8 %. Due to the high heat capacity of helium in comparison to the GGG, the trapping of helium inside the cooling channels of the core substantially reduces the available entropy variation. The designed core has a filling factor of 0.94 and a heat exchange area of 0.3 m^2 . The irreversibility of the heat resistance between helium and core during the isothermal phases reduces further the efficiency to 0.3 and the refrigeration capacity to 49 J.

To obtain high refrigeration power one has to run the cycle fast. This increases the helium flow rate and therefore the pressure drop across the core. In practice, the refrigeration power is limited because pressure drop sets lower bounds to the cycle time. The pressure drop was measured versus flow-rate for HeI and HeII in the designed core geometry. Full cycles taking into account the irreversibilities discussed are shown in Figure 4 for 10, 15, 20 and 25 W refrigeration power. The flow pressure drop ranges between 10 mbar for the 10 W cycle and about 70 mbar for the 25 W cycle. Table 2 gives a summary of the designed refrigeration cycles.

Table 2 Calculated performance of practical refrigeration cycles ranging from 10 to 25 W

Refrigeration power [W]	10	15	20	25	49*
t_{cycle} [s]	4.9	3.3	2.5	2.0	1.01
Δt_w [s]	0.9	0.6	0.4	0.3	0.27
Δt_c [s]	3.6	2.3	1.7	1.3	0.34
η_{cycle}	0.33	0.32	0.32	0.31	0.30

* unachievable due to excessive pressure drop

The duration of the isothermal magnetization Δt_w is short in comparison to the isothermal demagnetization Δt_c due to the better heat transfer at 4.5 K. The cycles were designed such that the pressure drop of both isothermal phases are about equal.

ADDITIONAL LOSSES

For performance optimization not only the irreversibilities directly connected to the Carnot cycle, but also the losses due to the different components of the machine were taken into account. They are listed below.

The finite time of 240 ms for opening and closing the valves is a further limitation of the machine reducing the cycle frequency and the refrigeration power from 25 W to 22 W. The magnet losses, containing the losses of the superconducting coil and the magnetic circuit, consist of a frequency-dependent eddy-current dissipation and hysteresis losses; they amount to about 13 W at 4.5 K for a cycle producing 22 W refrigeration at 1.8 K. The losses of the cryostat and current leads bring in another 6 W at 4.5 K.

STATUS OF THE PROJECT

The machine can be optimized for a maximum cooling power of about 22 W with an efficiency of 0.22, i.e. 60% of Carnot efficiency including component losses. All components of the refrigerator have been individually tested. The field produced by the magnet and the a.c. losses of the magnet were measured for quasi-triangular current cycles of varying frequencies and amplitudes [1]. Detailed tests were carried out with the displacer pump for the circulation of HeI. The operating characteristic was measured for different cycles and varying hydraulic resistance and the necessary strokelength was defined. The valves and their actuating mechanisms were tested. The data acquisition and control system has been defined and implemented on VXI instruments. All components perform well, their integration is in progress and first tests of the complete machine are due in the second half of 1994.

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Figure 1 Schematic diagram of the static magnetic refrigerator

Figure 2 A view of the magnetic refrigerator upon assembly

Figure 3 Entropy of GGG as a function of induction

Figure 4 Cycles including all irreversibilities varying refrigeration power