FR8203271

C.E.A.-C.E.N-G
D.R.F.C.-SPhIG
SERVICE DES BASSES TEMPERATURES
Laboratoire de CRYOTECHNOLOGIE

Le 5 Mai 1982

6350/3

NOTE SBT/LCT/26-82

THERMODYNAMICAL ANALYSIS OF A DOUBLE ACTING RECIPROCATING MAGNETIC REFRIGERATOR

A.F. LACAZE
A.A. LACAZE
R. BERANGER
G. BON MARDION

ICEC 9/ICM
Kobe, Japan 11,14 May 1982
CEA-CONF-- 6350

THERMODYNAMICAL ANALYSIS OF A DOUBLE ACTING RECIPROCATING MAGNETIC REFRIGERATOR

A.F. Lacaze, A.A. Lacaze, R. Beranger and G. Bon Mardion

CEA/CENG/DRFC/Service des Basses Températures - 85 X 38041 GRENOBLE, FRANCE

Methods of adiabatic demagnetization were limited until very recently to one-shot operations or to power levels below 1 mW. This paper describes the results of a reciprocating magnetic refrigerator operating between 1.8 K and 4.2 K, with a useful power greater than 1 watt.

In this type of machine there are various problems associated with heat transfer between magnetic substance and heat sources and inside the substance itself. The refrigerator described here overcomes some of these problems and achieves good efficiency.

EXPERIMENTAL DEVICE

The machine we used has already been described elsewhere (1). Its main part is a bar comprising two single crystals of gadolinium gallium garnet $Gd_3Ga_5O_{12}$ or G.G.G. (Fig. 1). The bar is moved vertically with an hydraulic jack controlled by a function generator. Both magnetic elements are moved periodically and subjected to a cycle consisting of magnetization up to a magnetic induction B at 4.2 K, and subsequent demagnetization down to 0 Tesla at 1.8 K. Inside the central He II bath, there are an electrical heater and an auxiliary liquid helium refrigerator which allow us to determine the useful power at 1.8 K and the different losses as function of the frequency ; we can also determine the heat released to the warm source at 4.2 K by measuring the liquid helium consumption. The drive system can be used to impart well defined movements to the bar. A high speed movement insuring quasi adiabatic process is followed by a low speed movement which allows good heat transfer. So the cycle performed in principle by the G.G.G. would be a carnot cycle (two isotropics and two isotherms).

HEAT TRANSFER AT THE HEAT SOURCES

The thermal conductivity of G.G.G. is very large, about 0.3 $Wcm^{-1}K^{-1}$ at 1.8 K (2) and the temperature homogeneity is always good inside the block of G.G.G. (2.4 cm in diameter) for all the frequencies involved. The thermal power absorbed by the magnetic elements from the cold source remains proportional to the frequency until the limitations coming from heat transfer at the sources are reached.

At the cold source heat transfer is limited by the Kapitza resistance. If we take for heat transfer the value computed with the theoretical phonon radiation limit, that is to say, a thermal power proportional to the 4 th power of the temperature, the maximum cooling power would be about 2 watts at 1.8 K with our two magnetic elements.

At the warm source the limitation comes mainly from the transition between nucleate and film boiling convection. The critical nucleate boiling flux is reached when the magnetic element is near 5.2 K ; in this condition the magnetic element would transfer a maximum thermal power of 30 watts to the warm source. This is realised when the temperature of G.G.G., at the end of the magnetization with high speed movement, i.e. when the element enters the bath at 4.2 K, is at a temperature slightly lower than 5.2 K. In this case any power limitation of the refrigerator would come only from heat transfer at the cold source. On the contrary, if the temperature of G.G.G. is greater than 5.2 K, heat is transferred with film boiling convection ; the maximum thermal power decreases sharply from 30 watts to about 3 watts. In this condition the limitation would come mainly from the warm source.

REAL CYCLE

The magnetic induction is produced by two main coils facing each other and two small compensating coils also facing each other. The magnetic induction profile is such that the whole bath at 1.8 K is in zero field (Fig. 2a). At the end of the high speed movement during the demagnetization process, the paramagnetic element is therefore in a zero field region. Then, in the lower temperature part of the cycle, the G.G.G. is thus subjected to an isofield increase of temperature.

Fig. 3 is an entropy diagram for G.G.G. for various magnetic fields. On it are superposed a Carnot cycle ABCD and four refrigeration cycles a, b, c, d. The four refrigeration cycles are computed for two maximum magnetic inductions and two frequencies. These computations take into account heat transfer in all parts of the cycle.

Before discussing the various refrigeration processes, it is desirable to have a method of comparing a real refrigerator with the ideal refrigerator. The cost of the work necessary to perform the cycle being negligeable compared to the cost of the refrigeration near 4 K, we can define a coefficient of performance : C.O.P. = Qc/Qw where Qc is heat absorbed from the cold source at Tc, and Qw is heat released to the warm source at Tw. For the ideal refrigerator or Carnot refrigerator, Qci/Qwi = Tc/Tw, and C.O.P.i = 42.6 %. For a refrigerator using a special cycle "o" the C.O.P.o is equal to Qco/Qwo Qco and Qwo being the thermal power exchanged with the two sources. If now, we take a real refrigerator, the useful power Qu is the electrical power released to the cold source. In the same way Qwr is the thermal power computed from liquid helium consumption and we have C.O.P.r = Qu/Qwr.

The figure of merit F.O.M. is still another means of comparing the performance of practical refrigerator, and is defined as :

$$FOM = COP/COPi = COP/0.426$$

we will have FOMo for the special cycle, FOMr for the real one.

High value of the maximum magnetic field

At high frequencies, heat transfer at the warm source is poor because of film boiling. So, as for the cold source, G.G.G. is rather subjected to an isofield heat transfer at the warm source, than to an isothermal one, the cycle is closer to the magnetic equivalent of the Joule cycle (two adiabatics, two isofields) than to Carnot cycle.

Low value of the maximum magnetic field

For magnetic field levels lower than a critical value, we have always nucleate boiling heat transfer at the warm source. At low frequencies there is no heat transfer limitation and G.G.G. can reach 1.8 K at the end of demagnetization in cold source and 4.2 K at the end of magnetization in warm source. The power removed from the cold source is thus proportional to the frequency. For high frequencies at the beginning of magnetization G.G.G. is always at a temperature lower than 1.8 K ; hence on entering the bath at 4.2 K, it is colder than that temperature. In the same way, at the beginning of demagnetization, in the warm source, the temperature of G.G.G. is greater than 4.2 K. As a consequence the power is no longer proportional to the frequency. During nucleate boiling heat transfer at the warm source, the temperature difference between G.G.G. and liquid helium is more constant than at low frequencies and the efficiency increases.

EXPERIMENTAL RESULTS

Fig. 4 compares the variation of useful power Qu as a function of frequency for different values of maximum induction B with a cold bath at 1.8 K ; on it are superposed the curves computed with the cycles shown in Fig. 3. From experiments we have determined dynamic heat losses Qd = 0.5 watt at 0.9 hertz and 2.5 Tesla and static losses Qs = 0.3 watt. The useful power being 1.2 watt we have Qcc = Qu+Qs+Qd = 2 watts. This value is close to the maximum cooling power computed with a theoretical value of Kapitza resistance. Still for 0.9 hertz, 2.5 Tesla we have :

COPr = 19 %   FOMr = 45 %   COPo = 27 %   FOMo = 64 %

In order to realise an engine operating in a Carnot cycle, it is necessary to have a special magnetic field profile. For the cycle ABCD reported on Fig. 3, if we want to have the same induction in A and C, that is to say, the same induction all along the bearing, induction in B is determined when induction is fixed in D and vice versa. For instance, if $B_D = 0$ then B_A and $B_C = 1.5$ Tesla and $B_B = 2.5$ Teslas. If we want to increase B_B we cannot have B_D at zero. We have reported fig. 2 b and c possible magnetic field profiles. As it was easier to adapt profile b was chosen for a new machine which uses the two main coils and the cryostat of the first machine.

CONCLUSION

The results obtained with our experimental reciprocating magnetic refrigerator show that now it is possible to have high power refrigerator with good efficiency in particular for the production of superfluid helium. Significant progress has been made in several technological areas : in particular improved knowledge of the thermal problems present in magnetic refrigerators.

REFERENCES

1 Lacaze, A.F., Beranger, R., Bon Mardion, G., Claudet, G., Delpuech, C., Lacaze, A.A., and Verdier, J., 'Proceedings of CEC 81 San Diego' paper HB6

2 Daudin, B., and Salce, B., 'Conductivité thermique de $Gd_3Ga_5O_{12}$' C.R. Ac. Sc. Paris 293 885 (1981).

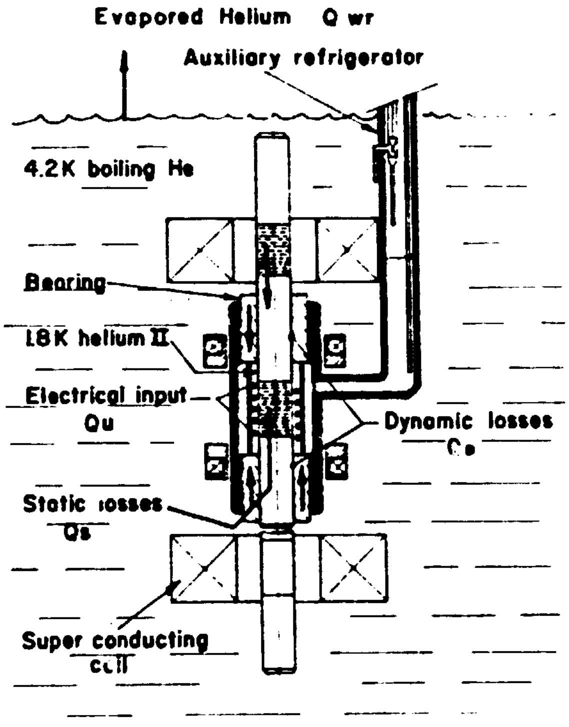

Fig. 1 Cross sectional view of experimental device

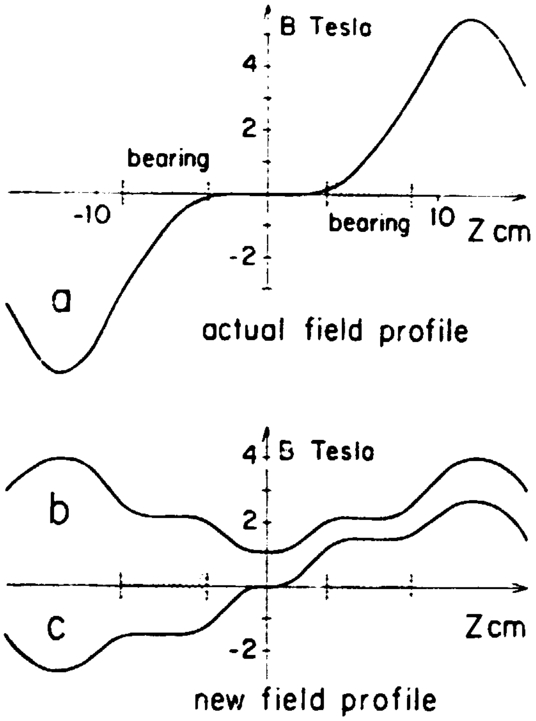

Fig. 2 Magnetic field profiles

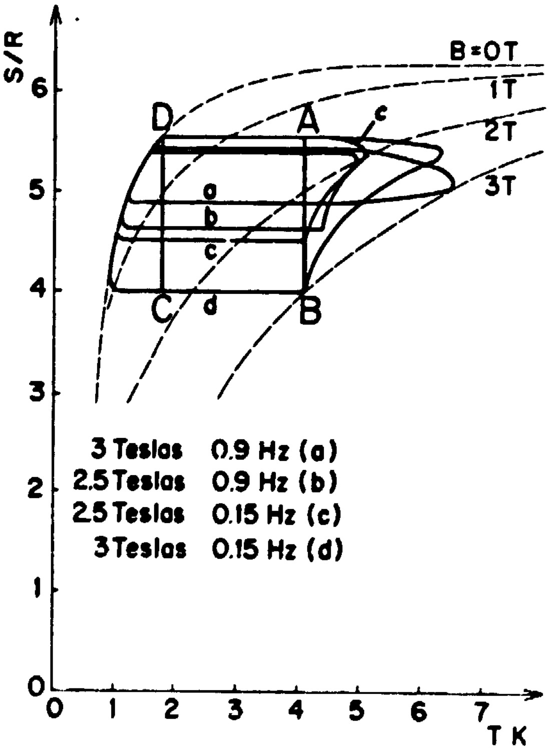

Fig. 3 Entropy diagram for $Gd_3Ga_5O_{12}$

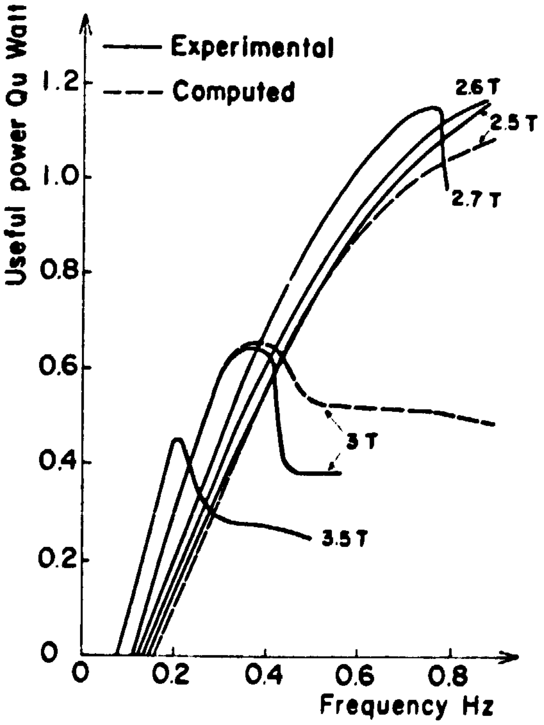

Fig. 4 Useful power at 1.8 K