LA-UR -82-1232

CONF-820814--14

LA-UR--82-1232

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MASTER

TITLE: THE EFFECT OF PARASITIC REFRIGERATION ON THE EFFICIENCY OF MAGNETIC LIQUEFIERS

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SUBMITTED TO: Intersociety Energy Conversion Engineering Conference, August 8-13, 1982, Los Angeles, CA

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THE EFFECT OF PARASITIC REFRIGERATION ON THE EFFICIENCY OF MAGNETIC LIQUEFIERS

by

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ABSTRACT

Our studies have shown that magnetic refrigerators have the potential to liquefy cryogens very efficiently. High efficiency is especially important for liquid hydrogen and liquid natural gas applications where the liquefaction costs are a significant fraction of the total liquid cost. One of the characteristics of magnetic refrigerators is the requirement for a high-field superconducting magnet. Providing a 4.2-K bath for this magnet will require a small amount of parasitic refrigeration at 4.2 K even though the rest of the liquefier may be at 110 K (liquid natural gas) or higher. For several different refrigeration power levels at 4.2 K, we have calculated the efficiency of the magnetic liquefier as a function of power, temperature and the 4.2-K refrigerator efficiency. The results show that if the ratio of the thermal load at 4.2 K to the main refrigeration power is 0.001 or less, the effect on the efficiency of the liquefier is negligible at all temperatures below room temperature provided the 4.2-K refrigerator efficiency is high.

INTRODUCTION

Magnetic refrigerators exploit the temperature and magnetic-field dependence of the magnetic entropy of a solid material to extract heat from a low-temperature source and transfer it to a higher temperature sink. The temperature change with field is called the magnetocaloric effect. This effect was discovered in paramagnets(1,2) and ferromagnets(3,4) more than fifty years ago. Until a few years ago, the main use of the magnetocaloric effect was to provide sub 1-K temperatures for condensed matter research. The advent of higher energy costs and the availablity of high-field superconducting magnets have led to efforts to apply this effect to refrigeration above 1 K(5-7) with the hope that cooling devices can be developed having considerably greater efficiency than present machines.

Existing refrigerators/liquefiers operating on various gas cycles have a rather low efficiency relative to Carnot(8), which directly affects the cost of cryogens that are used today. Liquid hydrogen and liquid natural gas (LNG) have particular importance as fuels. Increased liquefaction efficiency could significantly reduce the cost for these two fuels and could produce large savings for other potential applications. Recent magnetic liquefier model studies(9) indicate that a dramatic increase in efficiency might be possible if magnetic liquefiers could be made to span 4.2 to 300 K. The problems associated with realizing this potential are under investigation at the Los Alamos National Laboratory.

One of the major components of a magnetic liquefier system is a high-field superconducting magnet. The magnet, in turn, requires a super-insulated dewar and liquid helium even though the main refrigeration load may be at some higher temperature, e.g. 110 K for LNG. Fortunately, the magnetic work in the thermodynamic cycle is not put into the refrigerator by charging the magnet. Once the field is established the refrigerator magnet can operate in a persistent mode, and the current leads to the magnet can be removed to reduce the heat leak into the helium. The steady magnetic field eliminates charging losses that are caused by flux jumping and reduces eddy-current losses to a negligible level. The magnet requires an initial liquid-helium transfer, but thereafter the refrigeration requirement can be provided by a small magnetic-refrigerator stage from the primary cold temperature to 4.2 K. This extra parasitic refrigeration power will decrease the efficiency of the primary-stage refrigerator.

The purpose of this paper is to show the calculated results of the decrease in overall efficiency because of the parasitic refrigeration load.

METHOD OF CALCUALTION

The efficiency η in this problem is defined as the ratio of the real coefficient of performance (COP) to the ideal COP. The efficiency equation has its basis in rewriting the second law of thermodynamics as an equality, rather than an inequality, by the addition of a term for the irreversible entropy production.(10) The integral form of this equation is

$$\frac{Q_C}{T_C} + [illegible] \qquad (1)$$

[illegible] $+ Q_L + W$

where $\dot{Q}_c$ is the reversible cooling power; $\dot{w}_i$ is the rate of work dissipated in the refrigerator at temperature T (for example, pumping power); $\dot{q}_j$ is the rate of heat leak into the refrigerator from external sources; $(\Delta \dot{S}_{irr})_n$ are the internal, irreversible entropy production rates (for example, heat transfer across a temperature difference); and $\dot{W}$ is the rate of work required to operate the refrigerator. The calculations for the efficiency from this equation are model-dependent; and because no full-scale magnetic liquefiers exist yet, we have chosen to use the following simpler method to estimate the reduction in overall refrigerator efficiency. If we define COP (ideal) equal to $\dot{Q}_c/\dot{W}_c$ and COP (real) equal to $\dot{Q}_c/(\dot{W}_c + \dot{W}_L)$, the efficiency can be expressed as

$$\eta = \frac{1}{1 + \frac{\dot{W}_L}{\dot{W}_c}} \qquad (2)$$

where $\dot{Q}_c$ is now the main refrigerator cooling power, $\dot{W}_c$ is the work required to pump the main liquefier thermal load to room temperature, and $\dot{W}_L$ is the work required to pump the 4.2 K refrigeration load $\dot{Q}_L$ to room temperature. If we take both the main and the parasitic refrigerators as ideal and the hot temperature as 300 K, Eq. (2) can be used to calculate the minimum effect of the parasitic refrigeration on overall efficiency. Various ratios of 4.2-K load refrigeration to primary load refrigeration can be used to calculate the effect on overall efficiency as a function of temperature.

RESULTS AND DISCUSSION

The efficiency-vs-power curves for a variety of hypothetical magnetic liquefiers are shown in Figs. 1 and 2 for two different loads at 4.2 K.

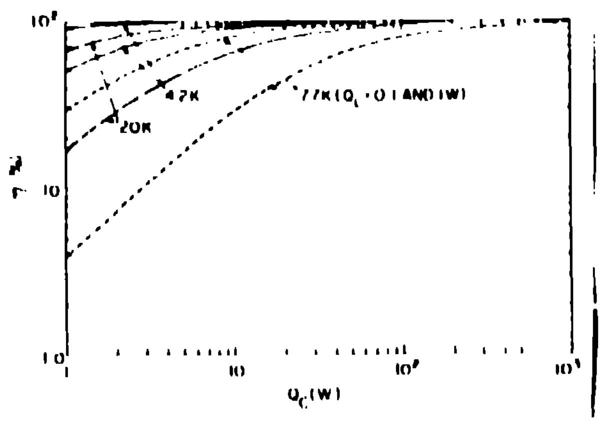

Fig. 1. Relative efficiency as a function of cooling power at 4.2 K, 20 K, and 77 K for parasitic loads of 0.1 and 1 W.

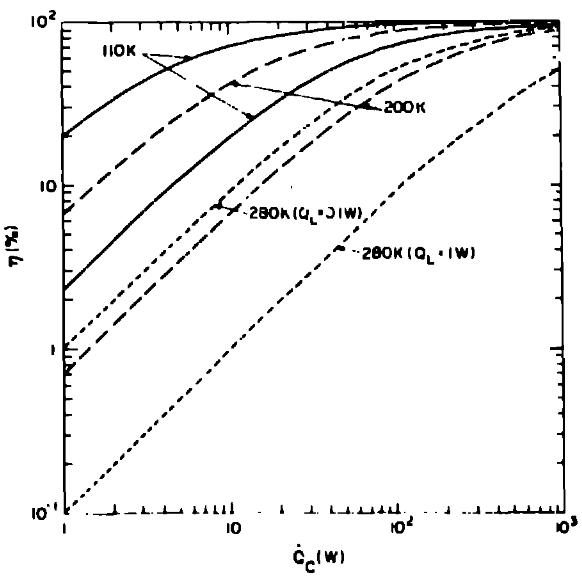

Fig. 2. Relative efficiency as a function of cooling power at 110 K, 200 K, and 280 K for parasitic loads of 0.1 and 1 W.

As expected, the parsitic refrigeration has virtually no effect on the overall efficiency of a refrigerator at any temperature provided the primary cooling power is large. However, as cooling power decreases the parasitic refrigeration decreases the overall efficiency with very large effects at higher temperatures or small capacities. Figure 3 shows the overall efficiency as a function of temperature for several ratios of 4.2-K load to primary load.

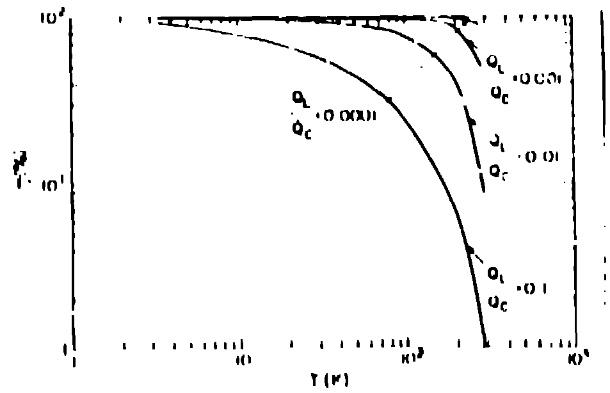

Fig. 3. Relative efficiency as a function of temperature for several ratios of parasitic load to main refrigeration load.

The results show that if $\dot{Q}_L/\dot{Q}_c$ is made small, either by good dewar design or by large cooling power, the effect of parasitic refrigeration is very small at liquid hydrogen and LNG temperatures and remains small to room temperature. As $\dot{Q}_L/\dot{Q}_c$ increases, the reduction in overall efficiency becomes dramatic, particularly near room temperature.

In order relate these results to possible magnetic lique designs, it is necessary to have an estimate $\dot{Q}_L$ and the size of a magnet c liquefier with capacity $\dot{Q}_C$. The parasitic load consis of heat leaks caused by radiation, conduction hrough supports, current leads, charging losses instrumentation and control wiring, conduct on by drive rods, etc. If radiation is the largest heat leak, the loss should be a function of surface area; but if other mechanisms, such as conduction through drive rods and supports, are also heat leaks, the loss will not be a function of surface area only. In magnetic systems, the current density of the magnet is also dependent on the size of the coil as well as the field magnitude. An emprical relationship of current density and stored energy describes most of the existing magnet systems very well. Because the magnetic-liquefier system has a dewar with both radiation and conduction losses and a superconducting magnet, the size of which depends on the cooling power, we believe that the best way to portray dewar heat leak for these systems is as a function of stored energy in the magnet. Some data available from the literature are summarized in Table I and shown in Fig. 4 as circled points. As there are many variables in the systems represented in Fig. 4, it is not suprising that there is an order of magnitude scatter in the data; however, a general trend is obvious. In most of these superconducting magnetic systems the dewar-refrigeration subsystem is a minor part of the total heat input, whereas in a magnetic liquefier the dewar/magnet will contribute a major part of the total heat input. Therefore, we believe that a curve through the lowest points on Fig. 4 will be an upper limit on the parasitic refrigeration load. A minimum heat leak can be established by taking the best high-performance dewar available and putting a reasonable magnet in about half of the volume. By using existing data on high performance dewars (e.g., 1%/day boil-off from 500 ℓ), we calculated the three diamond-shaped points on Fig. 4, which represent the lower limit of heat-leak rate into a magnetic liquefier system.

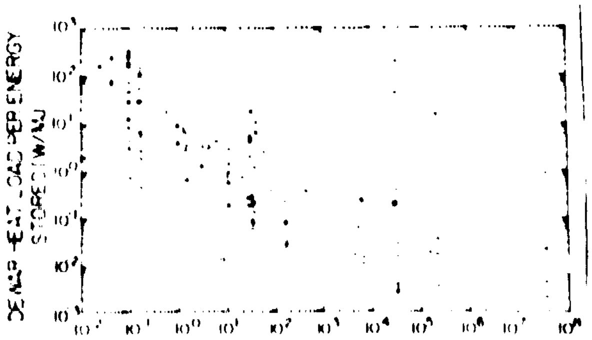

Fig. 4. The ratio of the parasitic heat load in magnetic systems to the energy stored in the magnet as a function of stored energy. The black dots are experimental results and the others are calculated.

In order to relate the stored energy in a magnet of a magnetic liquefier to the cooling power of the liquefier, it is necessary to look at the energy density of the working material. For a typical magnetic material like gadolinium, a 6-T magnetic field will cause an energy change of about 25 kJ/ℓ of gadolinium. From previous magnetic liquefier studies, a cycle frequency of 0.2 Hz appears reasonable, leading to 5 kW/ℓ of gadolinium. If size effects, such as porosity and field profile, cause the magnet volume to be twice the gadolinium volume, the cooling power is further reduced to 2.5 kW/ℓ or 2.5 MW/m^3. A 6-T field over 1 m^3 stores about 14 MJ; and from Fig. 4 we obtain an absolute minimum $\dot{Q}_L$ of 15 W and a more probable heat leak of ∿ 25 W. Thus, ratios of $\dot{Q}_L/\dot{Q}_C$ range from 6 x 10^{-5} to 1 x 10^{-3}.

Finally, the effects of less than ideal COP for the 4.2-K refrigerator are shown in Fig. 5, where overall efficiency is plotted as a function of the 4.2-K load refrigerator efficiency for three important temperatures. The additional reduction in efficiency is apparent, but its effects are not large because the 4.2-K refrigeration load is a small part of the overall cooling power.

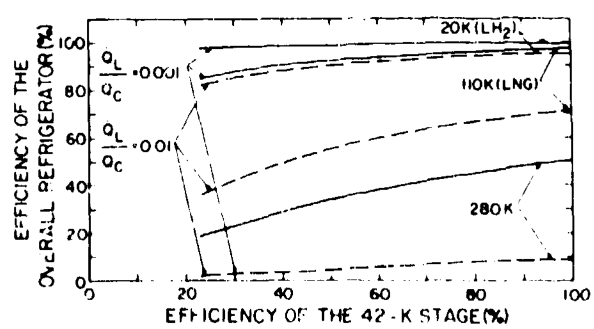

Fig. 5. The relative efficiency of the overall refrigerator as a function of the efficiency of the efficiency of the parasitic refrigerator stage.

SUMMARY

These calculations show that the parasitic refrigeration puts a lower limit on the practical size of magnetic liquefiers, with 1 W at 4.2 K being one approximate limit and 1000 W at 280 K being another approximate limit. The heat leaks from radiation and structural supports must be carefully minimized to reduce the effect on the overall efficiency, particularly for higher liquefaction temperatures or smaller capacities. At both liquid hydrogen and liquid natural gas temperatures, the parasitic refrigeration has very little effect for reasonable estimates of $\dot{Q}_L/\dot{Q}_C$.

TABLE I

SUMMARY OF ENERGY STORED AND HEAT LOADS FOR SUPERCONDUCTING MAGNET SYSTEMS

Energy Stored (MJ)	Heat Load (W)	Measured (M) or Calculated (C) Load	Reference
6 700	73.2[a], 712.8[b], 532.5[c]	C	11
~ 168	4.2[d], 1.0[e], 1.5[c], 2.4[b], 4.9[f], 180[g]	C	12
3	3.7[h]	M	13
1[i], 1.4[j]	6.5	C	14
	3.7[b,d,e], 8.5[b,c,d,e]	M	
10.9	2 to 6[a,k]	M	15
34.3[l]	2 to 3[h]	C	16
440	160[m], 45[n], 60[f] 45[b], 70[g], 80[o]	C	17
36	1.3[d], 0.5[f], 1.8[p], 0.7[o], 0.5[u], 3.0[c]	C	18
26.7	3[d], 2[e]	C	19
158,000[q]	250[e], < 200[g], 2400[f], 192[b]	C	20
1.5	5[a], 77.2[b]	C	21
0.6	10[a], 7[c]	C	22
223,000[q]	824[d], 2990[e], 2170[c], 502[b], 1500[f]	C	23
36,000,000	500, 3800, 75,000[d,r]	C	24
	14 400, 75,800, 683,000[e,r]	C	
34.2	2[c], 1[e], 1.3[d], 0.3[f]	C	25
6,100	60[c], 90[e], 85[d], 110[f]	C	25
4,480	43[c], 41[e], 35[d], 60[f]	C	25
80	30[h]	C	26
34	7[h]	C	26
160	35[h]	C	26
172	10[h]	C	26
690	145[d]	C	26
5,300	335[h]	M	26
0.045	10.7[a]	M	27
40.4	250[d], 100[e], 50[h]	C	28
0.025	3.8[a]	M	29
4.25	13[a]	M	30
30, 100	5104[a], 1086[e]	C	31
56.8	130	C	32
11	30	C	33
6710	135[h], 1300[g]	C	34
0.1	2.8[h], 17.8[h,u]	M	35
30	8[d], 50[e], 59[b], 10.7[c]	C	36
6[l]	25[h]	C	37
1.5	1[h]	M	38
6500	400[h], 190 000[h]	C	39
0.155	7.8[h]	M	40
0.1	1.208[h], 22.22[g]	M	41
0.165	0.995[h], 22.22[g]	M	41
50[v]	60[d], 30[e]	C	42
32.5	9.2[h], 556[g]	M	43
3.11	9.94[h]	C	44
0.1	< 7[d,e,f], 18[c]	C	45
33,800	1 308 000[t]	C	46
33,600[w]	84[d], 12[e], 492[f], 360[c], 5568[h]	C	47

[a]Dewar losses or dewar heat leak
[b]Electrical load
[c]Current lead cooling
[d]Radiation
[e]Supports
[f]Penetrations, instrumentation leads, standoffs, etc.
[g]Thermal radiation shield (LN_2)
[h]Heat Leak to LH_e
[i]Air Coil
[j]With iron yoke
[k]Depending on the LH_e liquid level
[l]Six coils in series
[m]Liquid nitrogen shield radiation
[n]Liquid nitrogen shield conduction
[o]Conduction in piping
[p]Conduction plus radiation at neck
[q]Twenty-four coils
[r]To 1.8 K, 20 K, and 77 K, respectively
[s]In persistent mode
[t]Steady state cooling
[u]Static and dynamic loads, respectively
[v]Ten coils
[w]Twelve coils

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