Technical Notes

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Optimization of Heat Rejection in Space

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Introduction

IT is demonstrated that the system mass required for radiation of (waste) heat from a thermal source to space can be reduced by rejecting the heat from a radiator at a temperature above that of the thermal source, using a heat cycle powered by a second heat source at a higher temperature than that of the source of waste heat. For temperature ratios of the second-to-first source on the order of 5, the total radiator area is reduced by a factor of 16 for Carnot cycles. Practical heat cycles may yield reductions as large as a factor of 10.

The Concept

Suppose that a heat load Q must be removed from a source that is at a (relatively low) temperature T_0. This temperature might be set, for example, by human tolerance or by the cooling requirements of the electronics. The proposition examined here is that it may be preferable, from the standpoint of minimizing overall system mass, to reject this heat to space at a temperature $I_r > T_0$ by means of a refrigeration system, which is in turn powered by a heat engine drawing heat from a source at temperature $T_s > T_r$, rather than rejecting it directly at T_0.

To examine this proposition, we compare the two systems shown schematically in Fig. 1. In system A, the heat is rejected directly at T_0 by thermal radiation and the required area for a blackbody radiator is

$$A_0 = Q/\sigma T_0^4$$

For system B, if P is the power delivered to the refrigerator,

$$A_r = (Q+P)/\sigma T_r^4$$

The power required depends on the coefficient of performance of the refrigerator. If it is a Carnot engine, $(Q+P)/Q = T_r/T_0$ and $P/Q = T_r/T_0 - 1$. To allow for nonideal performance, take $P/Q = (T_r/T_0 - 1)/\epsilon_r$.

The heat that must be rejected by the power-producing engine is $Q_r = [(1-\eta)/\eta]P$, where η is the efficiency of the engine, and for a Carnot engine $\eta = 1 - T_e/T_s$. Again, to allow for nonideal behavior we assume $\eta = \epsilon_e(1 - T_e/T_s)$.

Now, the *total radiator area* $A = A_e + A_r$ is

$$\frac{A}{Q} = \frac{1}{\sigma T_r^4}\left[\frac{(T_r/T_0)-1}{\epsilon_r}+1\right] + \frac{1}{\sigma T_e^4}\left[\frac{(T_r/T_0)-1}{\epsilon_r}\right]\left(\frac{1-\eta}{\eta}\right)$$

and in ratio to the area required for system A

$$\frac{A}{A_0} = \left(\frac{T_0}{T_r}\right)^4\left[\frac{(T_r/T_0)-1}{\epsilon_r}+1\right] + \left(\frac{T_0}{T_e}\right)^4\left[\frac{(T_r/T_0)-1)}{\epsilon_r}\right]\left(\frac{1-\eta}{\eta}\right)$$

or substituting for η

$$\frac{A}{A_0} = \left(\frac{T_0}{T_r}\right)^4\left[\frac{(T_r/T_0)-1}{\epsilon_r}+1\right] + \left(\frac{T_0}{T_e}\right)^4\left[\frac{(T_r/T_0)-1)}{\epsilon_r}\right]\left[\frac{1-\epsilon_r(1-T_e/T_s)}{\epsilon_e(1-T_e/T_s)}\right] \quad (1)$$

As we shall see, this ratio can be much less than unity, provided that T_r and T_e are substantially larger than T_0. Although this does not prove that the total mass of system B is less than that of system A, because the argument has thus far not included the masses of the refrigerator and engine or the relative masses per unit area, it is true for many such radiatively cooled heat engines, particularly at large power levels, that the radiator mass is dominant. Thus, to keep the argument simple, we shall *assume* the system mass is measured by the required radiator area.

Again, for simplicity initially, assume both refrigerator and engine are Carnot engines, then $\epsilon_r = \epsilon_e = 1$ and Eq. (1) becomes,

$$\frac{A}{A_0} = \left(\frac{T_0}{T_r}\right)^3 + \left(\frac{T_0}{T_e}\right)^4\left(\frac{T_r}{T_0}-1\right)\left(\frac{T_e/T_s}{1-(T_e/T_s)}\right) \quad (2)$$

Given T_0 and some (maximum allowable) T_s, there is the question of choice of the optimum values of T_r and T_e. A modest algebraic exercise shows that A/A_0 is a minimum with respect to variation of T_r/T_0 and T_e/T_0, for fixed T_s/T_0, if

$$\frac{T_r}{T_0} = \frac{T_e}{T_0} = \frac{3}{4}\frac{T_s}{T_0} \quad (3)$$

This result is familiar as the optimum ratio of radiator to source temperature for the heat engine alone.

Substituting this value for T_e/T_0 and T_r/T_0 in Eq. (2), we find

$$\left(\frac{A}{A_0}\right)_{\min} = \frac{4^4}{3^3}\frac{(T_s/T_0-1)}{(T_s/T_0)^4} = 9.48\frac{(T_s/T_0-1)}{(T_s/T_0)^4} \quad (4)$$

which is the primary result of this Note.

This area ratio is shown in Fig. 2 as a function of T_s/T_0 by the lowest curve, for which $\epsilon_r = \epsilon_e = 1$. We see that the

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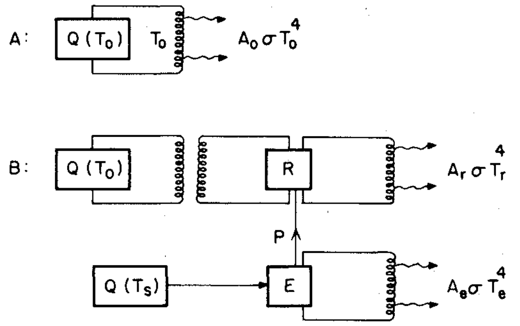

Fig. 1 Schematic diagrams of heat rejection systems: A) direct heat rejection and B) heat rejection via heat engine operating from source at T_s/T_0.

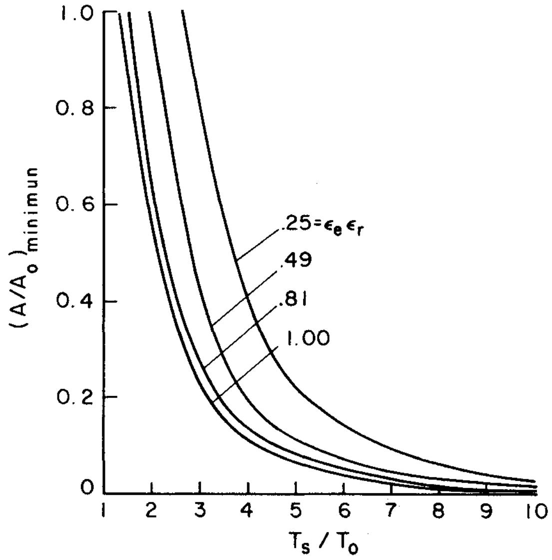

Fig. 2 Ratio of minimum radiator area to that for direct heat rejection, as a function of the ratio of the heat engine source temperature to the waste heat source temperature.

reduction in radiator area is about a factor of 16 for $T_s/T_0=5$ and a factor of 100 at $T_s/T_0=9$, which admittedly implies a high T_s.

The advantage is, of course, less for real engines than for Carnot engines. Assuming the same temperature ratios as for the idea case, we find for the (approximate) minimum radiator area,

$$\left(\frac{A}{A_0}\right)_{\min}\approx\left(\frac{4}{3}\ \frac{T_0}{T_s}\right)^4\left[1+\frac{3(T_s/T_0)-4}{\epsilon_r\epsilon_e}\right]$$

from which it is clear that $(A/A_0)_{\min}$ retains its approximate inverse cubic dependence on T_s/T_0. This result is also plotted on Fig. 2 for a range of values of the product $\epsilon_r\epsilon_e$. Current highly refined heat engines can achieve values of ϵ in the order of 0.6-0.7, so $\epsilon_r\epsilon_e=0.49$ is not unreasonable. For this case, we see a reduction in radiator area of about a factor of 10 for $T_s/T_0=5$. Reoptimizing the temperature ratios for the nonideal situation would decrease $(A/A_0)_{\min}$ somewhat.

Conclusion

While the magnitude of the gain that can be realized must be determined by quantitative design studies and, in any case, will depend on the temperature level of the heat source and on the degree of perfection of the refrigerator and engine, it does appear that substantial reductions in system mass can be realized by the heat rejection concept proposed here. In view of the high cost of transportation to orbit, the concept seems worthy of quantitative evaluation.

Recent Experiments with the Eindhoven MHD Blowdown Facility

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SIGNIFICANT enthalpy extractions were obtained in early power runs of the closed-cycle MHD blowdown facility at the Eindhoven University of Technology (EUT). During run 303 in the fall of 1981, a maximum electrical power output of 362 kW (enthalpy extraction of 7.2%) was attained.[1] However, during power runs in 1982-1984, the power output varied substantially from run to run and the power level of run 303 could not be reproduced. In 1984, the available data were analyzed and the conclusion was reached that the large spread in power output was caused by 1) imperfect mixing of the cesium seeding; 2) load resistors having significant self-inductance, thus hampering the creation of streamers; 3) metal inlet and outlet parts inside the magnetic field (for reasons of structural strength) leading to short circuiting in the outlet region; and 4) different levels of molecular impurities during the various runs.

Recent experiments with the MHD blowdown facility performed in October 1985 were very successful. In connection with the mentioned analysis, the following modifications were introduced: 1) the single atomizer (Hartman whistle principle) was replaced by a system with two atomizers; 2) load resistors with negligible self-inductance were installed; and 3) the first part of the supersonic diffuser was redesigned and built up from small boron nitride tiles bolted to the cooling plates (see Fig. 1). In addition to these modifications, it was planned not to use the first run of a measurement series for power generation, since the analysis had also shown that the first run always produces a large amount of molecular contaminants caused by the degassing of the walls of the MHD generator. Table 1 shows the parameters of the various runs of the recent measurement series. Particularly, it is clear that the amount of water contamination decreased significantly after run 701, although the numbers given for H_2O and N_2 during run 703 are still about a factor two higher than those measured during the test series in 1981.

It is clear from Table 1 that the resulting power outputs of measurement series 7 are, to a large extent, reproducible. Run 703 produced an electrical power output of 423 kW (see Fig. 2), to date the maximum in this facility. The electrical power generated in these experiments is also an order of magnitude larger than the power produced in any other similar closed-cycle (noble-gas) MHD experiment in the world. Further, it is very promising that the construction of the MHD generator and the first part of the supersonic diffuser did not create problems during this measurement series. The supersonic diffuser shown in Fig. 1 can be used for the next measurement series without repair or modification. The electrically isolating construction of the supersonic diffuser has apparently also led to a decreasing static pressure in the second half of the MHD generator, with the axial distance even at a power output of

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