CRYOCOOLERS FOR AIRCRAFT SUPERCONDUCTING GENERATORS AND MOTORS[*]

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ABSTRACT

The proposal by NASA to use high-temperature superconducting (HTS) generators and motors on future (~2035) aircraft for turboelectric propulsion imposes difficult requirements for cryocoolers. Net refrigeration powers of about 5 kW to 10 kW at 50 K to 65 K are needed for this application. A 2010 survey by Ladner of published work between 1999 and 2009 on existing Stirling and Stirling-type pulse tube cryocoolers showed efficiencies in the range of 10 to 20 % of Carnot at 50 K, much less than the 30 % of Carnot needed to make the concept feasible. A cryocooler specific mass less than about 3 kg/kW of input power is required to keep the cryocooler mass somewhat less than the mass of the superconducting machinery. Current cryocoolers have specific masses about 3 to 10 times this desired value, even for those designed for airborne or space use. We discuss loss and mass sources and make suggestions where improvements can be made. For Stirling and Stirling-type pulse tube cryocoolers, most of the mass is concentrated in the compressor. We show that higher frequency and pressure can have a major influence on reducing the compressor mass. Frequencies up to about 120 Hz and average pressures up to about 5 MPa may significantly reduce the overall cryocooler size and mass while maintaining high efficiency. Other suggestions for reducing the mass are also given.

KEYWORDS: Aircraft, cryocoolers, efficiency, machines, pulse tubes, regenerators, Stirling, superconductors, specific mass

INTRODUCTION

NASA has set the following performance goals for future transport aircraft: (1) reduced airport noise, (2) reduced emissions (both pollutants and greenhouse gasses), and (3) reduced fuel burn [1]. With reduced noise, aircraft could fly into and out of small centrally located metropolitan airports. To do so also requires a capability for short take-off and

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TABLE 1. Dates and technology development for future aircraft [1].

Generation	**Approximate date**	**Technology**
N+1	2015	Conventional tube & wing
N+2	2020	Unconventional hybrid wing-body
N+3	2030	Advanced aircraft concepts

landing (STOL). Future generations of aircraft are designated as N+1, N+2, etc., with N being today's technology. TABLE 1 gives the approximate time frame for new aircraft technology development to meet the NASA performance goals. The performance goals for N+3 aircraft set by NASA are very stringent, such as a 55 dB noise reduction, 75 % emission reduction, and a 70 % fuel burn reduction. One concept being investigated by NASA to meet the N+3 goals is a distributed turboelectric propulsion concept as illustrated in FIGURE 1 [2]. With this concept superconducting motors are used to drive propulsor fans distributed over much of the upper surface of the trailing edge of the wings. With current high-bypass jet engine technology, the fans connected to the engine provide about 85 % of the engine thrust with the trailing exhaust providing only 15 % of the thrust. The fan speed is limited to a few thousand RPM in order to prevent supersonic speeds at the blade tips. Electric power to the motors can be provided by two superconducting generators driven by high-speed gas turbines. The generators and turbines can be made very efficient and compact by running them at much higher speed than that of the motors. The generators and motors would be connected through an "electrical gearbox." This revolutionary concept, which decouples speed and torque, provides many control advantages in addition to the potential of meeting the N+3 performance goals.

The electrically driven propulsion system is feasible only if the electrical motors can be about the same size as, or smaller than, existing gas turbines. FIGURE 2 shows a comparison of power densities for electric motors and aircraft engines taken from data by Masson, *et al.* [3]. The values shown in this figure represent general trends, but values for various motors and engines can vary significantly. The specific power of gas turbine cores (without propulsor) for use on the Boeing 787 is about 16 kW/kg, whereas the specific power of most conventional electrical motors is limited to about 0.5 kW/kg, although very large industrial motors can have power densities up to about 3 kW/kg. Some electric motors developed for use on automobiles have power densities as high as 4.8 kW/kg [4]. Therefore, because of their low power density, conventional electric motors cannot be used for aircraft propulsion. High power density electric motors are a part of NASA and DoD research and development plans. Higher power densities require higher current densities in the conductors and/or higher magnetic energy densities in permanent magnets. The output

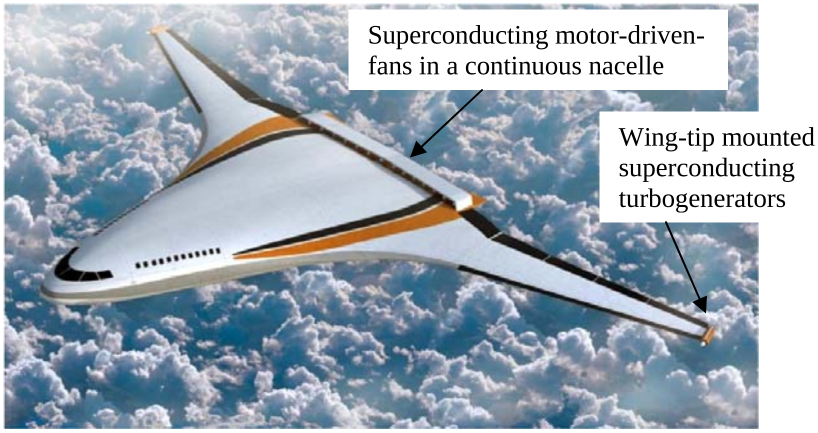

FIGURE 1. Artist's concept of future turboelectric aircraft utilizing superconducting generators and motors [2].

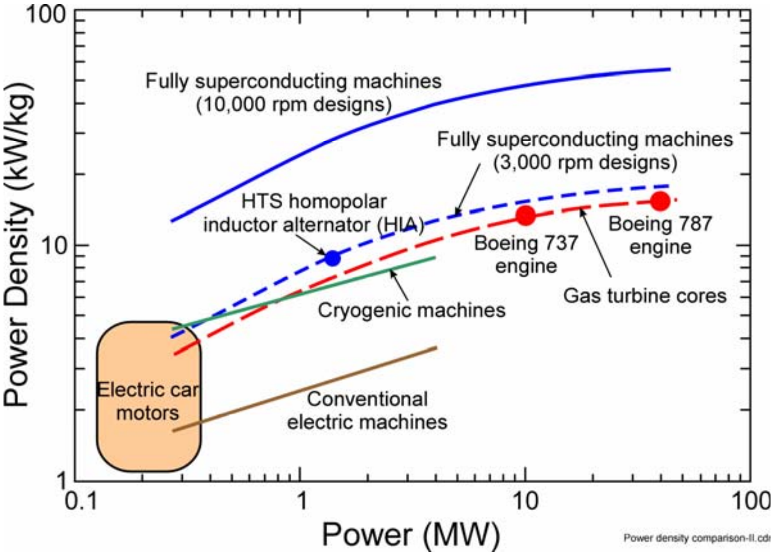

FIGURE 2. Power density comparison for gas turbines and electric machines.

power of a single generator for aircraft use may be as large as 30 MW [1].

Superconducting motors and generators offer the possibility of very high power densities and efficiencies because of the greatly reduced Joule heating. Current densities in superconducting BSCCO coils can be in the range of 10,000 to 20,000 A/cm^2 in a 2 T magnetic field. The newer YBCO superconducting coils can have even higher current densities. As a result, power densities are much higher, and at this time the highest power density of a superconducting machine is 7.8 kW/kg, achieved with a 16,000 rpm HTS generator developed for the Air Force [5]. At present, most HTS machines use superconductors only in the rotor where DC currents are used to produce a DC magnetic field, which interacts with an AC excitation in the copper stator windings. Designs for all-superconducting machines show typical power densities as high as 40 kW/kg for rotational speeds of about 10,000 rpm [3]. The use of HTS wire in the stator armature winding leads to significant AC losses in present YBCO materials. However, research on low AC loss HTS materials is quite active, so future motors and generators could become all superconducting at some time well before 2035. Superconducting machines require cooling with a cryocooler or with a cryogenic fuel, such as liquid hydrogen. This paper discusses cryocoolers for this application. Radebaugh and Ladner give a more detailed report [6]. Potential candidate cryocooler types are the Brayton, Stirling, and Stirling-type pulse tube. This paper focuses mostly on the latter two types of cryocoolers, although an approach to reduce the specific mass of Brayton cryocoolers is briefly mentioned here.

REFRIGERATION REQUIREMENTS

Refrigeration temperature and power

The use of superconducting machines onboard aircraft requires the development of reliable cryocoolers that also have high power densities. Many very small and very reliable cryocoolers have been developed for space applications, but their cooling powers are orders of magnitude less than those required for these aircraft applications. Large industrial cryocoolers or refrigerators have been developed that can provide the required refrigeration power, but no effort has been made to make those systems lightweight. Thus, it is difficult to determine whether existing cryocooler technology can meet the requirements for aircraft use. First, we must establish the requirements for the cryocooler, such as the operating temperature, the net refrigeration power, the maximum input power, and the maximum weight.

A superconductor normally operates within a three-dimensional space limited by magnetic field, temperature and transport current. The superconductor goes normal whenever any one of these limits is exceeded. To remain superconducting while carrying high currents, the superconducting wire must operate at temperatures well below the critical field value to allow for an adequate margin. For Bi-2223, or first generation HTS wire, the operating temperature must be around 30 K to 40 K. Second generation HTS wires, made with YBCO, can operate at about 50 K to 60 K. For N+3 aircraft operating around 2035, YBCO and possibly even better HTS wire would be available. For this study, operating temperatures of 50 K to 70 K are used as the goal to be provided by cryocoolers in future aircraft [7].

The heat load on the cryocooler for any HTS motor or generator consists mainly of (1) the active heat dissipation from the HTS winding due to AC losses, (2) heat conduction in the current leads, and (3) background heat leaks due to radiation and due to conduction through shafts and supports. One quality measure of any superconducting machine is the ratio of required refrigeration power to the electrical (generator) or mechanical (motor) power output of the superconducting machine. This quality measure can be defined as the cryogenic inefficiency of the superconducting machine, given by

$$\lambda_{sc} = 1 - \varepsilon_{sc} = \frac{\dot{Q}_{net}}{P_s}, \tag{1}$$

where λ_{sc} is the cryogenic inefficiency, ε_{sc} is the cryogenic efficiency, $\dot{Q}_{net}$ is the net heat load on the cryocooler, and P_s is the power rating of the superconducting machine.

The cryogenic efficiency is different from the overall efficiency of the motor or generator, which is given by the ratio of the output power to the input power. The difference between the input and output powers of an electrical machine is the total loss, which is in the form of heat. However, some of the losses in a superconducting machine will occur in the ambient-temperature components, such as the copper windings of the stator or hysteresis losses in iron. Also, the background thermal loss in a cryogenic system is not part of the overall loss associated directly with the superconducting machine. Published numbers for λ_{sc} in discussions of HTS machines are seldom reported, but such numbers would be very helpful in planning for future refrigeration requirements and sizing of cryocoolers. In 2009 Sivasubramaniam reported measurements with a 1.3 MW generator designed for airborne applications [8] that had a design power density of 8.8 kW/kg at full power. It was a HTS homopolar inductor alternator that utilized a stationary HTS field excitation coil, a solid rotor forging, and an advanced stator. The HTS coil for this configuration of generator operates with DC current, so AC losses are not important. The cooling requirement for this machine was 40 W at about 30 K. The cryogenic inefficiency for this machine is then $\lambda_{sc} = 3 \times 10^{-5}$. A 4 MVA generator developed by Siemens that used HTS for the rotating field coil required a refrigeration power of about 50 W at 30 K [5]. For this machine $\lambda_{sc} = 1.3 \times 10^{-5}$.

To achieve the very high power densities discussed earlier (as high as 40 kW/kg), all-superconducting machines (rotor and stator) would be necessary. In such machines, the cryogenic losses are dominated by the AC losses in the superconductor. AC losses in currently available YBCO tapes are much too high to consider their use in the armature, where large AC currents are required and high frequencies are needed for high rotational speeds. However, much research is underway to reduce AC losses in YBCO. When low AC loss YBCO becomes commercially available, such conductors could be used in future high-power density HTS machines for aircraft use. Barnes *et al.* [9] estimated total losses for such advanced machines. For a 5 MW machine, they estimated that the total loss would be about 500 W at 65 K, which results in a cryogenic inefficiency λ_{sc} of 1 x 10^{-4}.

For a 30 MW machine with a cryogenic inefficiency of 1 x 10^{-4} the heat load to 65 K would be 3 kW. A somewhat more conservative projection for AC losses in YBCO would have λ_{sc} = 5 x 10^{-4}, in which case the refrigeration power is 15 kW at 65 K. For demonstrations within the next ten years we may need up to about 10 kW of refrigeration at a temperature of 50 K. However, as advances are made in HTS, the required refrigeration power may decrease somewhat and the operating temperature may increase to about 65 K. For an aircraft with the size and power of the Boeing 737-200, the expected electrical power for thrusters would be about 10 MW, which requires 1 kW of refrigeration when the cryogenic inefficiency is 1 x 10^{-4}. For purposes of this report we focus on refrigeration powers in the range of 1 kW to 10 kW for temperatures in the range of 50 K to 65 K.

Input power and mass

Superconducting generators and motors offer many advantages for use on aircraft, but the power input and mass of cryocoolers required to maintain the necessary cold temperature results in a disadvantage for such systems. The overall system becomes successful only if the cryocooler input power and mass are small compared with the power output and mass of the superconducting machinery. We define these ratios as

$$X_P = \frac{P_c}{P_s} \tag{3}$$

and

$$X_M = \frac{M_c}{M_s}, \tag{4}$$

where P_c is the input power to the cryocooler, P_s is the power rating of the superconducting generator or motor, M_c is the mass of the cryocooler, and M_s is the mass of the superconducting machine. The power fraction of the cryocooler can be expressed in terms of the machine cryogenic inefficiency λ_{sc} and the second-law efficiency η_c of the cryocooler as

$$X_p = \frac{\lambda_{sc}(T_h - T_c)}{\eta_c T_c}, \tag{5}$$

where T_c is the cold temperature and T_h is the hot or ambient temperature of the cryocooler. FIGURE 3 shows how the power fraction varies with λ_{sc} and η_c for the case of T_c = 50 K and T_h = 300 K. (T_h could be reduced in flight.) This figure shows that cryocooler efficiencies of only 10 % to 20 % of Carnot yield power fractions less than 0.1 for $\lambda_{sc} <$ 0.001. However, we shall see in the following paragraph that to achieve low mass fractions, the cryocooler efficiency must be closer to 30 % of Carnot. For a net refrigeration power of 10 kW at 50 K, the input power becomes 167 kW when the efficiency is 30 % of Carnot.

The mass of the cryocooler can be expressed as

$$M_c = m_c P_c = m_c X_P P_s, \tag{6}$$

where m_c is the specific mass of the cryocooler (mass per unit of input power). When both sides of equation (6) are divided by the mass of the superconducting machine, we have

$$X_M = m_c X_P p_s, \tag{7}$$

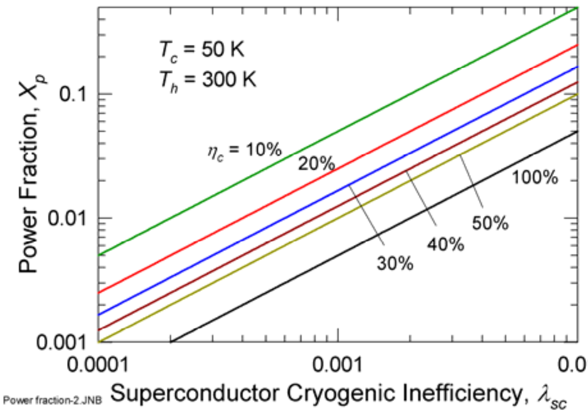

FIGURE 3. Ratio of cryocooler power to HTS machine power for various cryocooler efficiencies vs. cryogenic inefficiency of the HTS machine.

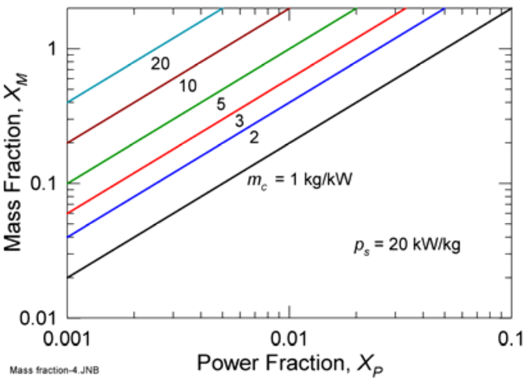

FIGURE 4. Ratio of cryocooler mass to HTS machine mass for various cryocooler specific masses vs. power fraction. HTS machine power density is 20 kW/kg for this figure.

where p_s is the power density of the superconducting machine. FIGURE 4 shows how the mass fraction varies with power fraction and the cryocooler specific mass for the case of a superconducting machine power density of 20 kW/kg. We note that with an expected power fraction of only 0.01, the specific mass m_c of the cryocooler must be less than about 3 kg/kW if the mass fraction is to be kept below about 0.6. Reducing the power fraction to 0.005 would allow the specific mass to be increased to 6 kg/kW for the same mass fraction, but the efficiency would have to be doubled to 60 % of Carnot for the same λ_{sc} and p_s. For a cryocooler specific mass of 3 kg/kW, the power density is 0.33 kW/kg. This power density is much less than that of conventional high-power electric motors, as shown in FIGURE 2. An alternate expression for equation (7) is $X_M = m_c{*}\lambda_{sc}p_s$, where m_c* is the cryocooler mass per unit of net refrigeration power. However, most of the cryocooler mass is that of the compressor, so m_c* becomes a strong function of the cryocooler efficiency.

SURVEYS OF EXISTING CRYOCOOLERS

In order to compare the efficiency and specific mass of existing cryocoolers to the requirements discussed in the previous section, we turn to the results of cryocooler surveys. A survey by Strobridge [10] in 1974 is often used as a comparison for any newly developed cryocooler. The extensive survey of 235 cryocoolers by ter Brake and Wiegerinck [11] in 2002 provides a valuable update of the Strobridge survey. However, many of the surveys lump cryocooler cold-end temperatures together, which result in 80 K cryocoolers dominating the reported performance. The recent survey by Ladner [12] shows how efficiency and mass vary with temperature. Ladner's survey included most new Stirling and pulse tube cryocoolers reported between 1999 and 2009.

Efficiency

FIGURE 5 shows how the efficiency of cryocoolers varies with refrigeration power. The lower curve in this figure is from the 1974 survey of Strobridge, and the upper curve is the upper limit of efficiency from the ter Brake survey [11], as given by Kittel [13]. This figure shows that in the range of 1 to 10 kW of refrigeration power, the maximum efficiency is about 20 to 25 % of Carnot and has not increased much in 35 years. FIGURE 6 shows data from Ladner [12] for the highest efficiencies of Stirling and Stirling-type pulse tube cryocoolers and how they vary with temperature. We note that maximum

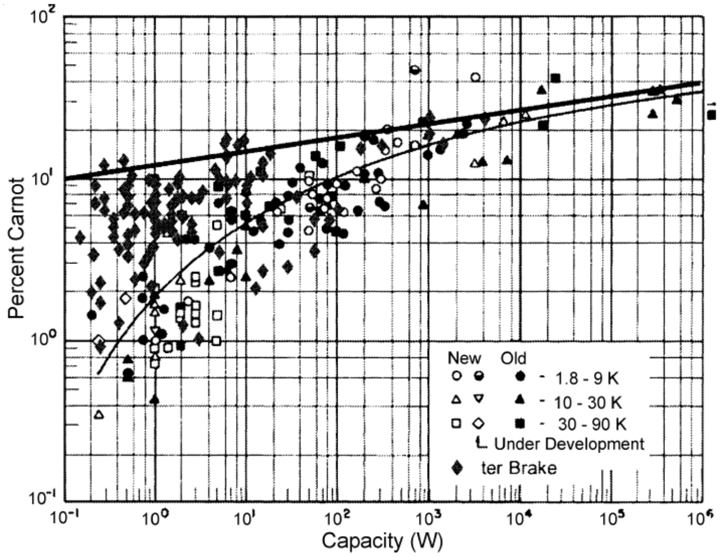

FIGURE 5. Cryocooler efficiencies from Strobridge [10] and ter Brake [11] with the upper solid line from Kittel [13] showing the maximum values. Capacity is the same as net refrigeration power.

efficiencies of about 25 % of Carnot are reported for Stirling cryocoolers in the temperature range of 50 K to 65 K, whereas pulse tube cryocoolers show maximum efficiencies in the range of 10 % to 15 % of Carnot in that temperature range. Most of these cryocoolers have refrigeration powers of only a few watts, although one of the pulse tube cryocoolers considered in the survey had a refrigeration power of about 1 kW, and two large commercial Stirling crocoolers of 1 kW and 4 kW at 77 K have efficiencies of about 25 % of Carnot in this temperature range. The largest Stirling cryocooler ever made provided 20 kW of refrigeration at 70 K with an efficiency of 41 % of Carnot [14]. Although this industrial cryocooler was much too heavy (49 kg/kW) for aircraft application, it shows that an efficiency goal of about 30 % of Carnot in large Stirling cryocoolers for temperatures of 50 K to 65 K should be realistic. Further research on large pulse tube cryocoolers is necessary to overcome flow nonuniformities if such high efficiencies are to be achieved.

Specific Mass

FIGURE 7 shows how cryocooler mass varies with input power from the CILTEC survey of ter Brake [11] and the Ladner survey [12] compared with the goal for aircraft use. The graph also shows mass data for five relevant cryocoolers with power inputs greater

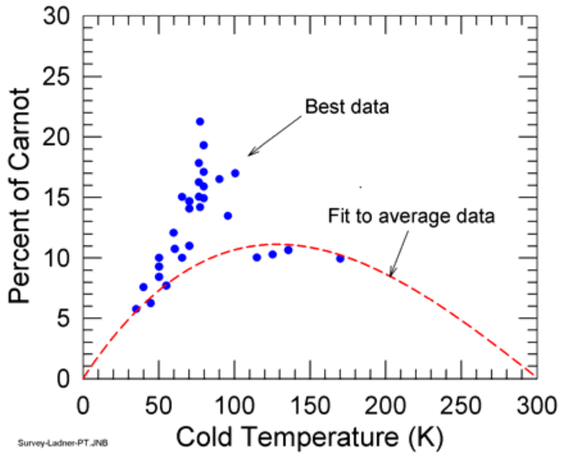

FIGURE 6a. Efficiencies of high-performance pulse tube cryocoolers from the Ladner survey [12].

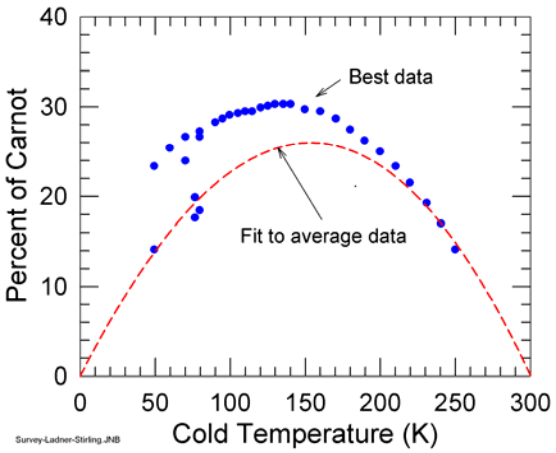

FIGURE 6b. Efficiencies of high-performance Stirling cryocoolers from the Ladner survey [12].

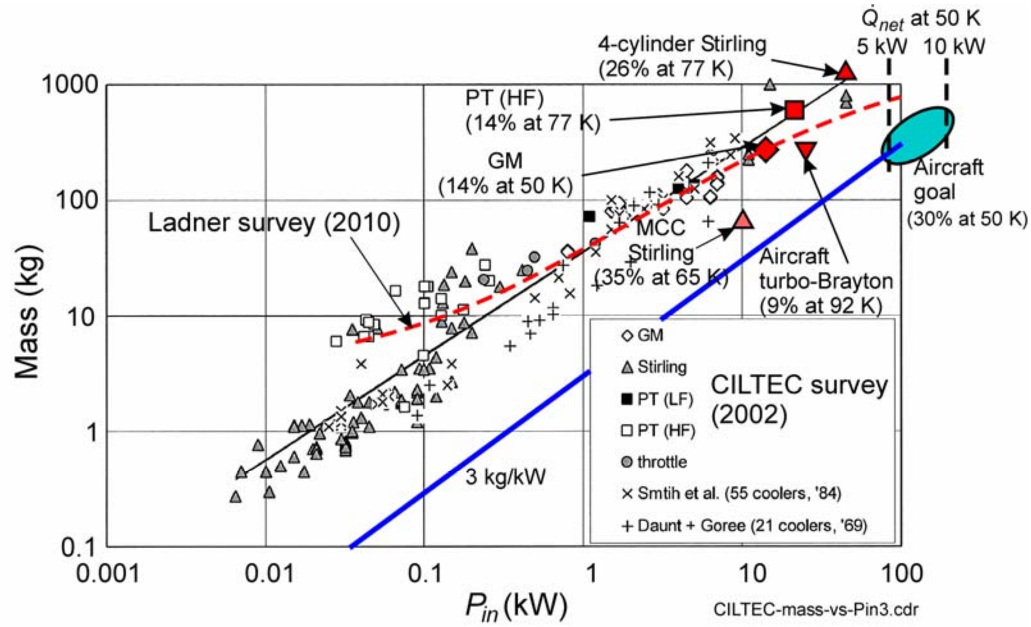

FIGURE 7. Comparison of cryocooler mass from surveys with mass goal for aircraft applications.

than 10 kW. The GM cryocooler is a large single-stage commercial cryocooler. The aircraft turbo-Brayton cryocooler was design for air liquefaction [15]. The 1 kW commercial pulse tube cryocooler is based on the work of Potratz, *et al.* [16] that uses a flexure bearing compressor for long life. The 4-cylinder Stirling cryocooler is a commercial kinematic version driven with a rotary motor and designed for industrial use [17]. The MCC Stirling cryocooler indicated in the figure is one under development for the Dept. of Energy, where the input and refrigeration powers are design values [18]. It is a unique design that uses three alpha-version Stirling cryocoolers that operate 120° out of phase in a three-phase arrangement, so three-phase power can be used directly to drive the cooler. In addition, the pistons are double acting, so both sides of the pistons are active. The backside of each piston is the pressure oscillator, and the front side with an insulating cap is the expander that receives gas from an adjacent piston. The mass of the cooler was estimated from dimensions of the three cooler modules and compared with similar sized pressure oscillators with known weight. The estimated 7.5 kg/kW specific mass of this cryocooler is only about twice that desired for aircraft use. This particular cooler was designed for ground-based applications of HTS machines or cables, so we expect that it could be made significantly lighter. These results show that considerable effort must be made to meet the 3 kg/kW specific mass goal for aircraft use.

METHODS TO REDUCE MASS

Because the specific mass goal is a greater challenge than the efficiency goal, we discuss here some approaches to reducing the mass of cryocoolers. Obviously, several engineering tasks include the use of high-strength and light-weight materials in place of the more customary materials wherever possible. Compact packaging arrangements, such as those used in the MCC Stirling cryocooler mentioned in the previous section, are also needed. Here we discuss three science-based approaches that could be useful in reducing mass.

Higher Frequency and Pressure in Regenerative Cryocoolers

The compressor accounts for most of the mass in Stirling and pulse tube cryocoolers. Operating them at higher frequency increases the power density proportional to the frequency. However, frequencies higher than about 60 Hz have usually resulted in significantly reduced efficiencies because of poor regenerator performance. Radebaugh and O'Gallagher [19] showed that high efficiency can be maintained at higher frequencies by simultaneously making the following changes to the operating conditions and the regenerator geometry: (a) decrease regenerator volume, (b) decrease hydraulic diameter, and (c) increase average pressure. Experiments with a 120 Hz pulse tube cryocooler verified that high efficiency can be maintained when the modifications discussed above are made [20]. FIGURE 8 shows calculated results for the cold-head efficiency of a 50 K regenerative cryocooler operating at 60 Hz and at 120 Hz. The peak values are at optimum conditions for each frequency. The calculations assume an expansion-space efficiency of 85 % due to nonisothermal processes in the expansion space (either a displacer or a pulse tube). For the same refrigeration power (same cold-end mass flow $\dot{m}_c$), the higher frequency leads to a smaller gas cross-sectional area A_g and a shorter length L. The regenerator volume and mass are reduced by a factor of three when increasing the frequency from 60 Hz to 120 Hz and the pressure from 2.5 MPa to 5.0 MPa. The higher pressure used for 120 Hz requires twice the tube wall thickness (taken into account in the calculations for efficiency), but the additional mass for the regenerator is negligible. The cold head efficiency decreases only slightly, from 42 % at 60 Hz to 38 % at 120 Hz. The higher frequency and pressure should lead to a compressor volume that is reduced by about a factor of four and a mass that is reduced slightly less than a factor of four due to the thicker walls needed for the higher pressure.

With the cold head efficiency of about 40 % of Carnot, the ambient temperature part (aftercooler and compressor) must be about 75 % efficient in converting electrical power into acoustic power at 300 K to achieve a total system efficiency of 30 % of Carnot. That requires careful matching of optimum compressor and optimum cold head acoustic impedances. It also requires a displacer to recover the cold-end acoustic power, which is about 17 % of the acoustic power at the regenerator warm end. A displacer is an integral part of the Stirling cryocooler, but it can also be used at the warm end of the pulse tube in a pulse tube cryocooler.

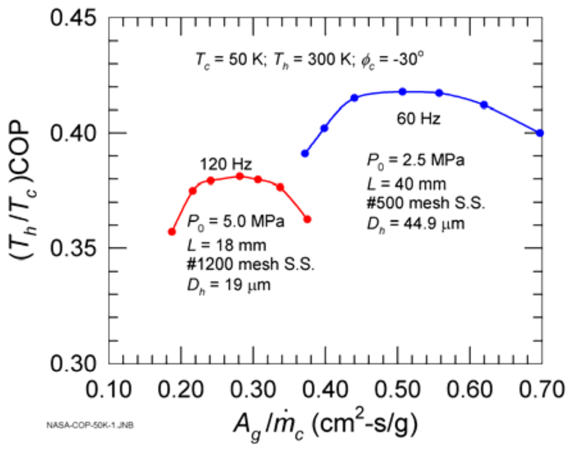

FIGURE 8a. Calculated second-law efficiency of a regenerative cryocooler cold head at 50 K optimized for a frequency of 120 Hz and 60 Hz vs. specific area.

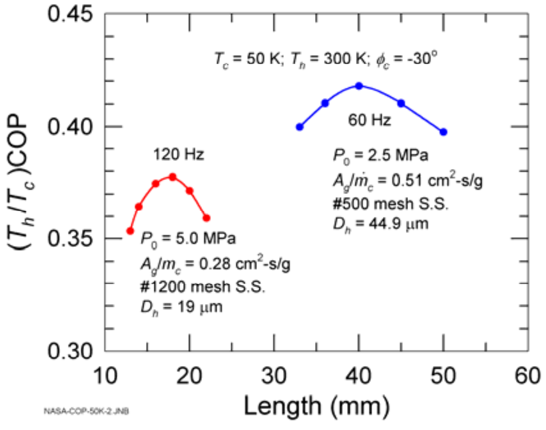

FIGURE 8b. Calculated second-law efficiency of a regenerative cryocooler cold head at 50 K optimized for a frequency of 120 Hz and 60 Hz vs. length.

Higher Pressure and Pressure Ratio in Brayton Cryocoolers

The Brayton cryocooler is a recuperative type with steady flow and pressure. For long-life space applications, centrifugal compressors and turbo-expanders supported on gas bearings are used. Such devices work best at low pressures and pressure ratios, which lead to low power densities. However, the very high rotation speed of the compressor and expander (1000 to 4000 rev/s) compensates for the low pressure and results in very high power densities for the compressor and expander. In the recuperative heat exchanger, the relevant power density is the Gibbs free energy flow per unit volume flow rate, which for an ideal gas is given by

$$g_v = \frac{\dot{n} R_0 T \ln(P_H / P_L)}{\dot{V}} = P \ln P_r, \tag{8}$$

where $\dot{n}$ is the molar flow rate, $\dot{V}$ is the volume flow rate in the heat exchanger, R_0 is the universal gas constant, T is temperature at any location, P_H is the high pressure, P_L is the low pressure, P_r is the pressure ratio, and P is the pressure in the flow channel of interest. The low pressure side (typically about 0.1 MPa) of the heat exchanger has the lower power density and will dominate the size of the heat exchanger. With the low pressures and pressure ratios (about 1.6) used in turbo-Brayton cryocoolers, the power density in the heat exchanger is very low, so the heat exchanger is the largest and heaviest component in the system. The low power density also requires very high effectiveness in the heat exchanger to yield high cryocooler efficiency. Research on ways to use higher pressures and pressure ratios in Brayton cryocoolers is needed to reduce their specific mass to 3 kg/kW. Multistage turbines could provide higher pressure ratios, but would add to the cost.

Low-Mass Linear Motors for Regenerative Cryocoolers

About 80 % of the mass of large Stirling or Stirling-type pulse tube cryocoolers is due to the pressure oscillator (compressor) [6, 12]. Presently about 30 % of the compressor mass is due to the linear motor. As efforts are made to reduce the mass of the compressor through the use of lightweight materials, the motor mass could make up 50 % of the compressor mass because of the requirement for using high density magnets, iron, and copper. About 50 % of the linear motor mass is due to the iron in most conventional linear motors [6]. Thus, research into ironless linear motors could lead to low-mass compressors. The use of a Halbach array [21] for the permanent magnets is one approach that can be used to eliminate the back iron in a linear motor [22]. In a Halbach array a set of permanent magnets are arranged with the magnetization direction rotated by 90° with each adjacent magnet, as shown in FIGURE 9. The magnetic field lines nearly cancel on one side of the array and are combined and amplified by a factor of about 1.4 on the other side

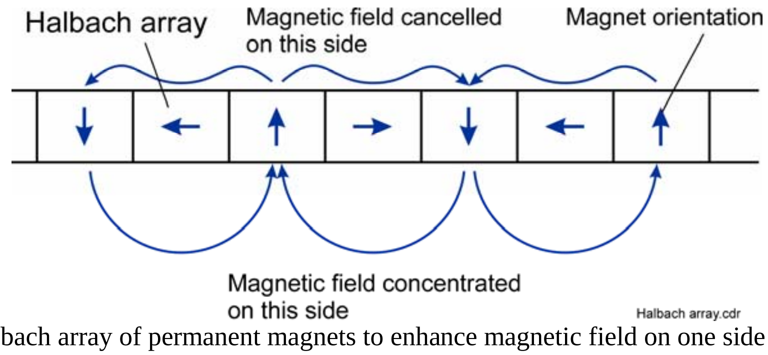

FIGURE 9. Halbach array of permanent magnets to enhance magnetic field on one side and cancel field on other side.

compared with a conventional array [22]. The higher field leads to an increase by a factor of two for the power density, and no back iron is required in the magnetic field path. A second Halbach array parallel and near the first array results in a very high field between the two arrays with very little field on the outside. For a cylindrical device the arrays can be curved into a circle with the use of magnetized arc segments. A comprehensive study of power density of a linear motor with Halbach arrays would be very useful. A superconducting linear motor [23] is also a possible option to increase the power density of a linear compressor, but it complicates the startup procedure before the cryocooler reaches the low temperature necessary for the superconducting linear motor to become effective.

CONCLUSIONS

Transport aircraft with significantly reduced airport noise, emissions, and fuel burn are desired and planned for the year 2035. One proposed approach to meet these goals relies on distributed turboelectric propulsion in which two high-speed gas turbines drive close-coupled superconducting generators that power a set of distributed lower-speed propulsor fans driven by superconducting motors. The superconducting machines will require about 1 to 10 kW of refrigeration at about 50 to 65 K. This paper shows that cryocoolers for this application need to have an efficiency of about 30 % of Carnot and a specific mass less than about 3 kg/kW of input power. Surveys of recent cryocoolers show that most high-efficiency cryocoolers have efficiencies of about 20 % of Carnot and specific masses of about 10 to 30 kg/kW. Considerable research is needed to meet the low specific mass goal. The use of lightweight materials, higher frequencies, higher pressures and higher pressure ratios are suggested to meet such goals. Innovative approaches to the elimination of iron in cryocooler motors can also lead to reduced mass.

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