Cryogenic system options for a superconducting aircraft propulsion system

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Abstract. There is a perceived need in the future for a move away from traditional aircraft designs in order to meet ambitious emissions and fuel burn targets. High temperature superconducting distributed propulsion may be an enabler for aircraft designs that have better propulsive efficiency and lower drag. There has been significant work considering the electrical systems required, but less on the cryogenics to enable it. This paper discusses some of the major choices to be faced in cryocooling for aircraft. The likely need for a disposable cryogen to reduce power demand is explained. A set of cryocooling methods are considered in a sensitivity study, which shows that the feasibility of the cryogenic system will depend strongly on the superconducting technology and the aircraft platform. It is argued that all three aspects must be researched and designed in close collaboration to reach a viable solution.

1. Introduction

There is a strong focus within the research and development organizations of the commercial aviation sector on the improvement of aircraft emissions and noise. ACARE Flightpath 2050 [1], equivalent to NASA N+3 goals, set reduction targets of 75% CO\textsubscript{2}, 90% NO\textsubscript{x} and 65% perceived noise emissions compared to a year 2000 baseline. Although a significant portion of these reductions are expected to be met by improvements in engine technology, it is likely that fully meeting the targets will require a move away from the traditional aircraft configuration to more radical solutions.

Distributed propulsion is an overarching description for propulsion concepts in which the propulsors (fans or propellers) are relocated away from the gas turbine engines. This can allow the exploitation of aerodynamic effects to the advantage of propulsive efficiency or lift generation, and can enable the hybridization of energy sources to lead to improved operating conditions for the engines.

Electrical distribution of propulsive power is of particular interest due to the design freedom it offers. The drawbacks are the additional system weight and loss mechanisms, which must be significantly outweighed by the benefits the system brings. It may be necessary to use a partly or fully superconducting system, from generators through to motors to achieve sufficient power density and efficiency. Early research into this area is being carried out by numerous organizations and many publications have explored the possibility of distributed propulsion concepts using high temperature superconducting distribution. In particular, NASA’s N3-X hybrid wing body aircraft has been subject to many such studies, notably by Armstrong et al. [2] and Felder et al. [3]. Isikveren et al. [4], Gibson
et al. [5] and Berg et al. [6] have also produced notable system-level studies into similar concepts. Luongo et al. [7] provided a clear introduction to the concept of HTS propulsion systems. Brown [8] has begun setting technology targets for superconducting aircraft propulsion system components.

Less focus has thus far been given to the cryogenic system that supports a superconducting electrical system in aircraft. This is a crucial contribution to the overall feasibility of a superconducting aircraft propulsion system and it is argued that research into the subject must be prioritized in conjunction with the major electrical components and in particular the aircraft-level design research. Radebaugh [9] has given valuable technology targets for cryocoolers in aircraft but this topic is highly complex and the design space for the solution of cryocooling high power superconductors in aircraft is considerable. This paper discusses some of the technical challenges and targets that have been elucidated in early studies of the subject. The research discussed is part of a technical assessment and is not indicative of future product developments.

2. Cryogenics for a superconducting aircraft propulsion system

The tree-shaped architecture, Fig. 1, with AC transmission, is a simplified example of the type of system under consideration. The use of AC/AC converters may be necessary to allow the electrical control of individual or groups of fan motors but could be avoided to reduce complexity and mass at the expense of control [6]. An architecture with DC transmission may be necessary if the cable AC losses are unmanageably high – a subject that will be difficult to resolve before the superconducting materials technology, cryogenics and necessary power electronics are more firmly established.

![Figure 1. Simple AC tree architecture for half system](image)

Gas turbine engines can still be present under the wings of the aircraft or can be integrated into the aircraft. These will drive large, superconducting generators and around half the required aircraft thrust will be provided via 8 smaller, electrically driven fans positioned at the rear of the aircraft fuselage. A commercial airliner requires between 5 and 100 MW of thrust power depending on its size.

2.1. Cryogenic architectures

The main possible philosophies for cooling a superconducting network such as this can be divided into three options:

1) Fully decentralised: Cooling is performed locally, so each machine or subsystem of components has a closed cooling loop with a cryocooler.
2) Partly centralised: Major coolers provide a medium-temperature circuit and localised cryocoolers provide cooling down to operating temperature.
3) Fully centralised: Large cryocoolers maintain a closed loop of cold fluid at the superconducting operating temperature.

Previous studies [10] have indicated that reciprocating cryocoolers are likely to be unsuitable for larger scale applications, although they are in common use for low power aerospace applications. Scalability and reliability will be crucial for the main cryocoolers used in scheme 2) or 3) and indications are that reverse-Brayton cycle cryocoolers would be best suited [11].

There is expected to be a general improvement in cryocooler power density with overall input power [6]. Under the assumption that insulation losses in the cooling circuit are small compared to
machine losses, it is likely that option 3) will lead to the lightest and most efficient system. A centralised cooling system is therefore preferred and is the subject in this paper.

2.2. Overall technology targets
The way in which an electrical propulsion system will benefit the aircraft performance is an ongoing area of research which is carried out in parallel with the electrical system studies. Technology targets at this stage can therefore only be indicative. Isikveren et al. [4] found an aircraft with boundary layer ingestion enabled by an aft-fitted gas turbine gave a 9% net reduction in block fuel burn. The additional equipment led to a 3.5% increase in operating empty weight (OEW) and only 0.1% increase in maximum take-off weight (MTOW) due to the reduced fuel requirements for flight. NASA’s N3-X studies give an estimate of a 16% gross fuel burn reduction due to BLI and improved propulsive efficiency before additional weights and inefficiencies are taken into account [8].

Further benefits could be made through the use of energy storage to allow more optimal operation of the gas turbines, but it is likely that the overall electrical system in an electrically distributed propulsion aircraft must be more than 90% efficient for aerodynamic benefits to become available. For a superconducting system, which uses unconventional technology to be seen as desirable, one must expect the target for the end-to-end system efficiency to be better than 95%. This leads to a target cryogenic system power of 2-3% of total electrical system power, leaving the remaining 2-3% to machine and transmission losses and power electronics.

With regard to mass, any increase has a direct impact on the aircraft drag and therefore power demand. Fuel savings, if sufficient, must offset the additional system mass and the MTOW should not grow significantly due to its large effect on major component sizing. Any increase will have positive feedback effects throughout the aircraft design. A total electrical system mass of more than 10% of OEW is unlikely to yield benefit. The cryogenics may be expected to make up around 2/3rds of the electrical system mass.

2.3. Operating temperature and superconducting material
It is a general trend that the current-carrying capacity of superconductors will improve with decreasing temperature. Though YBCO and BSCCO are superconducting at the boiling point of nitrogen (77 K), they may not perform sufficiently at these temperatures to allow sufficient machine performance.

It appears likely at this stage that the operating temperatures for the systems in question would lie between 15 and 50 K. The critical temperature of MgB₂ is 39 K and reasonable engineering performance can be expected below 30 K. MgB₂ wires show good potential for creating windings and can be filamented to reduce AC losses, so are considered an attractive option to pursue if possible. For this reason, the initial target temperatures will be 20-30 K unless it is shown that the aircraft-level solution will be better at higher temperatures.

2.4. Heat sinks
The question of how to dispose of the waste heat in the superconducting system and the associated cryocooling system will have a major impact on the overall aircraft design and its eventual performance. Simple calculations show that using ambient air, even at high altitudes, as the final heat sink will lead to challenging design constraints, in particular due to the low thermal efficiency that can be achieved. Since there will be electrical benefits for the superconducting components using the lowest possible temperature, the trade between efficient and light cryocooling and the low temperatures that minimize AC losses and material usage will be important. It is likely, for these reasons, that carrying a cryogen will be beneficial or necessary to enable a superconducting propulsion system. Table 1 shows the variation of power demand with cold operating temperature, $T_c$, fraction of Carnot efficiency achieved by the cryocooler, $\eta_{fc}$, and the heat sink temperature based on machine losses at cold temperatures of 0.1%. Cryocooler power demand, $P_{cc}$, is calculated with

$$P_{cc} = \frac{Q}{\eta_{fc}} \left( \frac{T_H - T_c}{T_c} \right)$$

(1)
where $\dot{Q}$ is the thermal load at cold temperature. The lighter regions represent cryocooler power demand of around 2% of system power or less. It is noted that ground operating temperatures can reach 325 K.

### Table 1. Comparison of cryocooler power demands as a percentage of system power, depending on heat sink temperature and fraction of Carnot efficiency achieved

| $T_c$ (K) | Power demand (kW) | $\eta_{fc}$ | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
|-----------|--------------------|-------------|-----|-----|-----|-----|-----|
| 60        | 5.5%               |             | 1%  |     |      |      |     |
| 50        | 7.0%               |             | 1.8%|     |      |      |     |
| 40        | 9.3%               |             | 3.1%|     |      |      |     |
| 30        | 13.0%              |             | 4.3%|     |      |      |     |
| 20        | 20.5%              |             | 6.8%|     |      |      |     |
| 15        | 28.0%              |             | 9.3%|     |      |      |     |

### 3. Technology sensitivities and targets

#### 3.1. System under investigation

An initial sensitivity study is presented to discuss the importance of the main technology performance parameters affecting the cryogenic system based on a centralized cooling architecture for cooling an abstracted superconducting system. Static models of single and two-stage cryocooler topologies were developed, as well as a more complex two-stage topology with intercooled compressors on both stages in a parallel configuration, Fig. 2. These are considered for the role of centralized cryocoolers when using LH$_2$ or LCH$_4$ heat sinks. The low temperature heat exchanger represents what would be a complex arrangement of heat exchangers and pipes collecting the component losses.

It is noted that the possible configurations of cryocoolers are manifold and that those chosen as examples here have not been conclusively shown to be viable as real solutions, except that the static modelling results give reasonable temperature and pressure values under the component performance assumptions used in the calculations.

The electrical system losses at cold temperatures are represented by a machine inefficiency assumption applied to the main motors and generators. Insulation losses and cable AC losses of the entire system are assumed to be small for the purposes of this study. The AC-AC converters may be cooled by spent heat sink fluid, which would, given correct design, improve the power electronics efficiency and reduce the temperature change required between cables and converters.

The heat sink coolant required is calculated based on the latent heat, $L$, and a minimum specific heat, $C_p$ of the heat sink using

$$m_{hs} = \frac{\dot{Q}}{(L + \Delta T_{hs} C_p)}$$  

(2)
where $\dot{Q}$ is the heat flux to be delivered to the heat sink and $\Delta T_{hs}$ is the change in temperature of the heat sink after evaporation. This indicates the need for a heat exchanger that allows both phase change and gas to gas heat exchange. The total fluid required is based on a 5-hour mission. The possibility of sub-cooling the heat sink fluid has not been considered here, but may be an additional degree of freedom in the system design. The heat sink is assumed to be kept at 1 bar and boiling point.

3.2. Parameters considered

The variables considered in this study are given in Table 2. A range of values bracketing the currently expected technological outcome is given with the nominal values in bold. The turbine polytropic efficiency is taken always to be 3% higher than the compressor efficiency. A different range is used for the gravimetric efficiency of the LH$_2$ tank and the LCH$_4$ tank to reflect the higher density and temperature of LCH$_4$ and the reduced concern due to leakage.

| Parameter                                                                 | Units                        | Values                           |
|--------------------------------------------------------------------------|------------------------------|----------------------------------|
| Machine inefficiency (thermal losses as a percentage of electrical power) | %                            | 0.03, 0.05, 0.07, 0.1, 0.2       |
| Compressor and turbine polytropic efficiency (Turbine +3% of values)     | %                            | 84, 87, 90, 92, 95              |
| Heat exchanger pressure drop (of fluid on both sides of the heat exchangers) | %                            | 10, 7, 5, 3, 2                  |
| Heat sink tank gravimetric efficiency (% of full tank mass made up of the stored heat sink fluid) | % | 20, 30, 40, 50, 60 |
| Heat exchanger minimum hot to cold side temp. differential               | K                            | 5, 10, 15                       |
| Max. cold operating temperature (highest temp. allowed at the cold components) | K                            | 20, 25, 30                      |
| Cryocooler total power density (mass per unit shaft input power)          | kg/kW                        | 5, 4, 3, 2, 1                   |
| Motor power density (output power per unit mass)                          | kW/kg                        | 5, 10, 15                       |

3.3. Sensitivity results

The models were combined and run for each variable range while holding the values of the remaining variables at nominal. The response to variation is generally linear, so the sensitivity of the system to the variables can be represented by the linear regression coefficient at nominal values, Table 3. The proportion of cryogenic mass and power vs. MTOW and system power are given. Note, the aircraft OEW can be approximated as half the MTOW. Figure 3 shows the variation of the system mass relative to nominal values with each variable being changed separately. The steepness of each line is indicative of sensitivity, while the length of each line is indicative of the uncertainty in the range into which the value might fall.
Table 3. Regression coefficients for single stage (1S), two-stage (2S) and two-stage with intercooling (2SI) systems

| Mass (M) / Power (P) | 1S (LH₂) | 2S (LCH₄) | 2SI (LCH₄) |
|---------------------|-----------|------------|------------|
| Cryogenic system % of MTOW/system power with nominal values | 1.6% | 5.3% | 5.5% | 5.5% | 4.2% |
| (4) Machine inefficiency at cold temperatures | 1.6 | 1.0 | 5.3 | 5.6 | 5.5 | 4.2 |
| (1) Compressor polytropic efficiency (Turbine +3%) | 1.7 | 0.3 | 27.6 | 33.3 | 26.5 | 22.3 |
| Heat exchanger pressure drop | 0.2 | 0.0 | 0.7 | 0.9 | 1.1 | 1.0 |
| (3) Heat sink tank gravimetric efficiency | 1.2 | 0 | 8.2 | 0 | 12.8 | 0 |
| Heat exchanger minimum hot to cold side temp. differential | 0.0 | 0.1 | 1.4 | 2.7 | 1.5 | 1.2 |
| (2) Maximum component operating temperature | 1.9 | 0.3 | 6.3 | 8.0 | 4.6 | 4.0 |
| Cryocooler total power density | 0.1 | 0 | 3.5 | 0 | 2.6 | 0 |
| Motor power density | 0.0 | 0 | 0.1 | 0 | 0.1 | 0 |

Figure 3. Effect of tested variables on system mass as a percentage of MTOW
Nominal mass is 5.3% of MTOW

3.4. Discussion
The comparison made here is subject to a large number of assumptions and uncertainties, so the numerical results can only guide further research. The most influential variables are labeled with numbers (1)-(4) in Table 3. The effect of these variables on the cryocooling system mass, when using the two-stage cryocooler without intercooling are shown in the nested contour plots in Figure 4. It is notable that the machine inefficiency will severely restrict the scope for a feasible system solution. The maximum machine operating temperature, which is varied under the assumption that it has no effect on machine inefficiency, also has a marked impact and it is clear that higher permissible temperatures would quickly reduce the demands on other aspects of the technology. It is shown that technology performance better than the nominal values in Table 2 are likely to be needed to allow a system with a LCH₄ heat sink to be viable.

The cryogenic system mass and power show that a cryocooler with intercooling is expected to be more efficient. However, outcome at system level indicates the heat sink mass flow rate required will have a significant bearing on the system mass. A higher system-level mass is reached due to LCH₄ and tank despite the assumption of an equal power density, which does not take into account the additional complexity of the cryocooler. The increased LCH₄ demand of the intercooled cryocooler, due to lower
maximum temperature being reached, makes the system mass very sensitive to the tank gravimetric efficiency.

Below the nominal technology variables, the indication is that a liquid hydrogen cooling system will be required due to the reduced cryocooling power demand and the requirement of only a single stage cryocooler or none at all. Purely open-loop cooling using LH₂ has not been considered here, but remains a possibility provided the less localized use of LH₂ can be shown to be safe. Drawbacks of LH₂ use will be greater expense, additional engine complexity if it is combusted or the need for fuel cell equipment, and possible handling concerns. The low density of LH₂ means, at nominal values, the LH₂ required take up 40% of the volume of the kerosene for a 5-hour flight. Any increases in thermal losses will soon lead to the need for compromises in the aircraft design to accommodate the tanks for longer missions. Cyclic loading, insulation and pressure containment may present difficult design challenges for lightweight LH₂ tanks. Note that the results are applicable to the superconducting system discussed in this paper and cannot be seen as general to all propulsion system designs. For example, the areas of acceptable mass may change if a different proportion of the thrust is produced electrically, or the aerodynamic and propulsive benefits are shown to be lower or higher.

4. Conclusions
This paper makes a tentative argument for a baseline method of cooling for superconducting distributed propulsion. The cooling is performed with centralised cryocoolers to allow scaling to improve power density. Reverse-Brayton cryocoolers appear most suitable. The target temperatures are 20-30 K to allow sufficiently power dense and efficient machines. A cryogenic heat sink is likely
to be required to limit cryocooler power demand and LCH₄ or LH₂ are the most promising options. LCH₄ may be an attractive option if certain technology targets can be reached. LH₂ requires slightly less stringent technology targets, but would be more limited by volume, expense and infrastructure.

A sensitivity study shows that, among the uncertainties currently surrounding the cryogenic system technology, the maturity of superconducting machines and materials and cryogen storage tanks are extremely important. Compression and expansion efficiency in the cryocoolers is shown to be important, but other major cryocooler assumptions are somewhat less significant. The requirement for large quantities of cryogenic heat sinks and the reliance of the system on superconducting technology being highly efficient means it is vital for the airframe and the electrical and cryogenic systems to be developed and optimised in a collaborative and integrated manner.

Acknowledgments
The research leading to these results was carried out under the DEAP (Distributed Electric Aerospace Propulsion) project which was undertaken by a consortium of Airbus Group Innovations, Rolls-Royce and Cranfield University, and was part-funded by Innovate UK. The work in this paper also received funding from the People Programme (Marie Curie Actions) of the European Union’s Seventh Framework Programme (FP7/2007-2013) under REA grant agreement 608322. The authors would like to thank Nicolas Fouquet, Peter Malkin and our other colleagues in the DEAP project.

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