A Performance Comparison of Hydrogen Aircraft Concepts

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Abstract

GKN Aerospace is committed to sustainable aviation. This paper considers the relative merits of cryogenic power distribution within a centralized power generation system for regional aircraft. Alternative schemes based on non-cryogenic high voltage power distribution and de-centralized power generation are considered and compared against metrics that include safety, performance and scalability.

Not only does the cryogenic, centralized system offer appreciable system mass reductions but it can also be more robust when specific safety and certification criteria such as fuel starvation and high energy rotating debris are considered. This emphasises the importance of integrated system design within a notional aircraft platform within a preliminary system design process.

GKN Aerospace have shown a cryogenic, centralized option to be scalable to aircraft carrying up to 160 passengers. While payload is scalable, increasing range is limited by the volume available for centralised, safe fuel storage within the rear fuselage. This is likely to be a limiting case for all hydrogen fuelled aircraft including combustion platforms. A robust modelling capability for a hydrogen fuel cell aircraft using both PACE APD software and in-house codes has been developed.

Keywords: hydrogen, fuel cell, aircraft design, cryogenic

1. Introduction

GKN Aerospace has made a substantial commitment to the development of sustainable aviation at the earliest opportunity. As part of that commitment and with UK Government support, a team at the new GKN Global Technology Centre in Bristol are investigating the development of hydrogen fuel cell Electric Propulsion (H2EP) with fuel cells and cryogenic power distribution; the Hybrid Hydrogen and Electric Architecture (H2GEAR) programme [1], [2].

A hydrogen fuel cell propulsion system offers the benefit of zero emissions apart from the water vapour that occurs naturally as a result of the reaction between hydrogen and the atmosphere within the cells. This lack of harmful emissions, including NOx, makes this propulsion system of particular interest for future aircraft concepts. The H2GEAR team have explored the safety and scalability of the proposed system concept. Ground tests of the end-to-end system to a 1MW power level will be completed before the end of the programme.

To have measurable environmental impact before 2050, the challenge has been to determine the potential aircraft applicability i.e. passenger number and operational range, that could be achieved and the potential Entry-Into-Service (EIS) dates. During the last 12 months, the H2GEAR team have completed successful Preliminary Design Reviews on both a 48 passenger propeller aircraft and a 96 passenger ducted fan aircraft. The knowledge gained from those platform designs has enabled the advantages and scalability of the cryogenic H2EP system to be understood.

The power and propulsion system concepts have been based on generic low temperature (LT-PEM) and intermediate temperature (IT-PEM) fuel cell stacks. A centralised approach has been adopted for all the notional platforms. This implies that only electrical power is distributed through the aircraft together with elements of the inert cryogenic system. All hydrogen paths are protected in safe unpressurised zones in the rear fuselage.

1.1 Development of Notional Platforms

GKN Aerospace have built the capability to model hydrogen fuel cell aircraft using the PACE APD software application [3]. Based on the results from numerous design iterations within H2GEAR it has been possible to develop mass functions that represent the key powertrain components as a function of required shaft power. Rather than having to perform top down and bottom up system mass iterations between APD estimates and a detailed bill of materials, the system can now use the APD environment to generate a converged solution in a single pass. The powertrain itself includes both fuel cell stacks and hybridised battery sources to provide all propulsive and systems power.

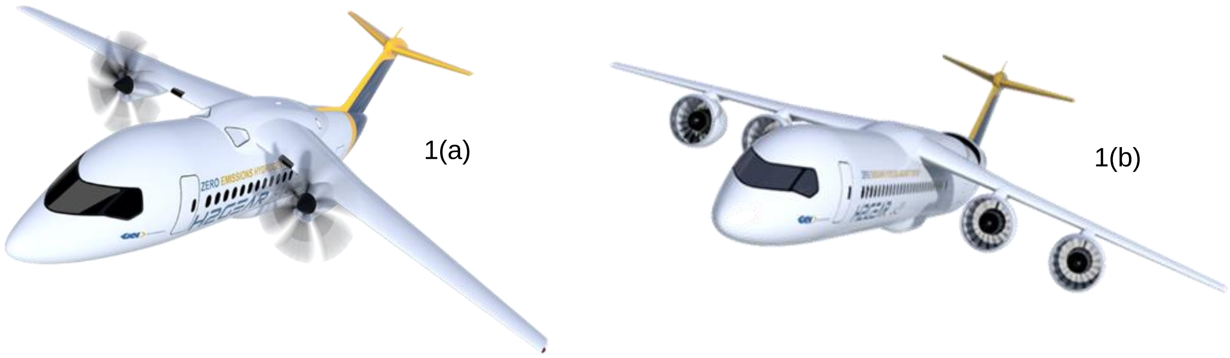

Figure 1 - (a) the GKN48 propeller aircraft, (b) the GKN96 ducted fan aircraft

The 48 passenger aircraft shown in figure 1(a) has been shown to carry that payload over a range of 900NM at a cruise condition of 25,000ft and Mach 0.45 with a design take off mass of 23,000kg. The propeller installation provides excellent low speed performance and an opportunity for an early Entry Into Service (EIS) date that does not depend on significant improvements to fuel cell performance.

The 96 passenger aircraft shown in figure 1(b) has been shown to carry that payload over a range of 1600NM at a cruise condition of 30,000ft and Mach 0.6 with a design take off mass of 44,000kg. The low pressure ratio ducted fans not only deliver high efficiency but also offer significant reductions in both cabin and far-field noise with reduced system complexity. All H2GEAR aircraft models assume standard reserves including contingency fuel, diversion and hold phases.

Both aircraft are configured around a standard single aisle cabin layout with a 3+3 seat arrangement. There is an advantageous trade between increased fuselage drag due to a reduced length:diameter ratio and the increased fuel storage capacity. All power generation and fuel conditioning is located in the rear fuselage behind the rear pressure bulkhead in safe, unpressurised zones, thus minimising any risk from hydrogen or cryogen leakage.

In order to properly account for all the aircraft loads, the power equilibrium conditions shown in figure 2 have been adopted.

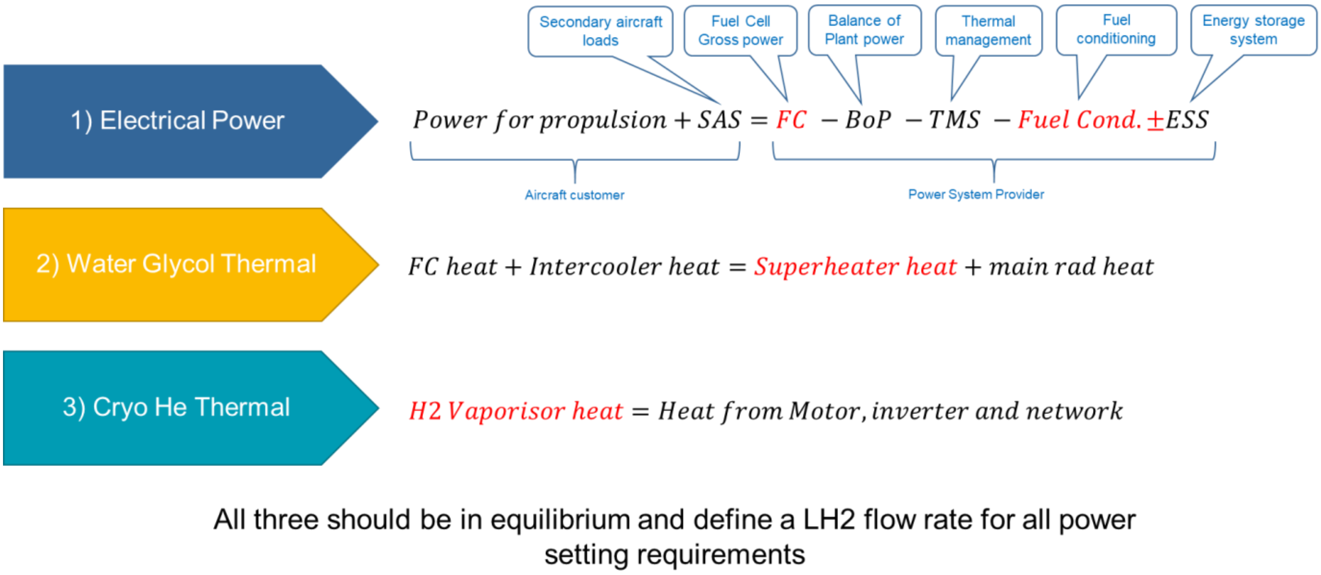

Figure 2 - Power equilibrium conditions

1.2 Objectives of the present study

The results generated by H2GEAR design iterations on a range of notional aircraft platforms from 19 passengers to 160 passengers with ranges up to 1600NM suggests that a centralised hyperconducting propulsion system is mass efficient, scalable and compliant with how CS-25 will develop for hydrogen based aircraft.

To support this view GKN Aeropace have undertaken studies to compare and contrast the H2GEAR system against both conventional electrical power distribution (i.e. non-cryogenic) and de-centralised concepts. De-centralised concepts being characterised by the distribution of hydrogen in either liquid or gaseous form, to thrust generating nacelles containing either complete power generation systems or gas turbine combustion systems.

The objectives of this study are:

a) to quantify the benefits of hyperconductivity in terms of the overall propulsion system mass for both a 48 and 96 passenger notional platform and,

b) to identify the key performance and operational functions that discriminate between centralised and de-centralised system concepts and,

c) to consider the scalability of both as aviation seeks a single aisle replacement that provides a significant contribution to meeting the global 2050 emission targets.

2. The GKN Aerospace Centralised Hyperconducting System

Figure 3 is a schematic of the proposed GKN hyperconducting system.

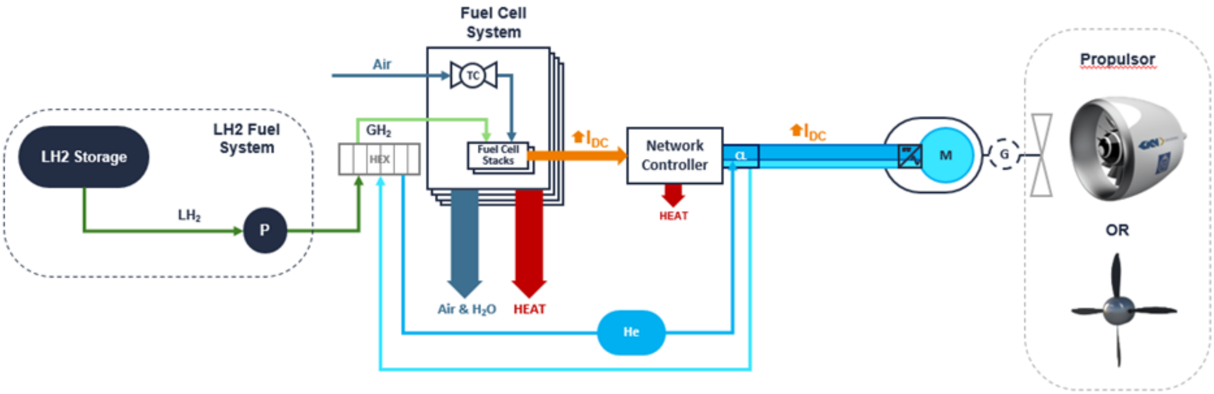

Figure 3 - The GKN cryogenic hyperconducting propulsion system

2.1 Liquid hydrogen fuel storage

To meet the basic range, payload and speed targets, hydrogen is stored as a cryogenic liquid in double wall tanks at around 20K and subsequently converted to a gaseous supply at the required temperature (above 300K) for the fuel cells. The inner tank of the system is vacuum encased by the outer tank. Studies are ongoing regarding the material selection for both inner and outer tanks.

Bulk storage of gaseous hydrogen at high pressure is very inefficient in terms of gravimetric index (GI) for anything beyond small general aviation aircraft. GI is defined as the ratio of the total fuel mass divided by the sum of the fuel and tank masses.

2.2 Hyperconducting electrical power distribution

The H2GEAR system is advantageous as its high efficiency cryogenic electrical distribution and power conversion (compared to a conventional non-cryogenic powertrain) enables a reduction in net fuel cell power output as well as reducing the amount of energy which is stored within the cryogenic hydrogen fuel system (i.e. reduced fuel burn) compared to more conventional, ambient temperature electrical systems.

The voltage standard for the hyperconducting system under investigation has been fixed at +/-270v. That standard is well established and previously certified in aerospace. It provides benefit in terms of avoidance of arcing and partial discharge effects at altitude thereby reducing insulation requirements, cable sizing selection and wiring segregation requirements.

2.3 Fuel Cell Power Generation System

The Intermediate Temperature Proton Exchange Membrane (IT-PEM) liquid cooled fuel cells use the supplied hydrogen and air to produce electricity with high current and low voltage, with heat as a by-product. The generated DC electrical power is conditioned for distribution within the aircraft but uses the cryogenic source as a cooling capability to minimise the size and mass of the conductors and electronics. Within the thrust nacelles the DC power is converted to AC and used to drive cryogenically cooled electric motors that can drive either propellers or ducted fans.

The amount of heat produced by the fuel cells is determined by their operating efficiency. At 50% efficient the cells will produce the same amount of heat as power. There is an important trade between the efficiency of the stack operating point and the size of the thermal management system. This is a factor of the polarisation curve of the specific cells. Operating at high efficiency will require more fuel cells but less thermal management and vice versa.

Air is supplied to the cathode of the fuel cells from a turbo-compressor system and a thermal management system has been defined and sized to dissipate the excess heat developed within the H2EP system. The management of waste heat has to be analysed over the entire flight profile that must include extended ground operations and a suitable temperature variation with altitude, figure 4.

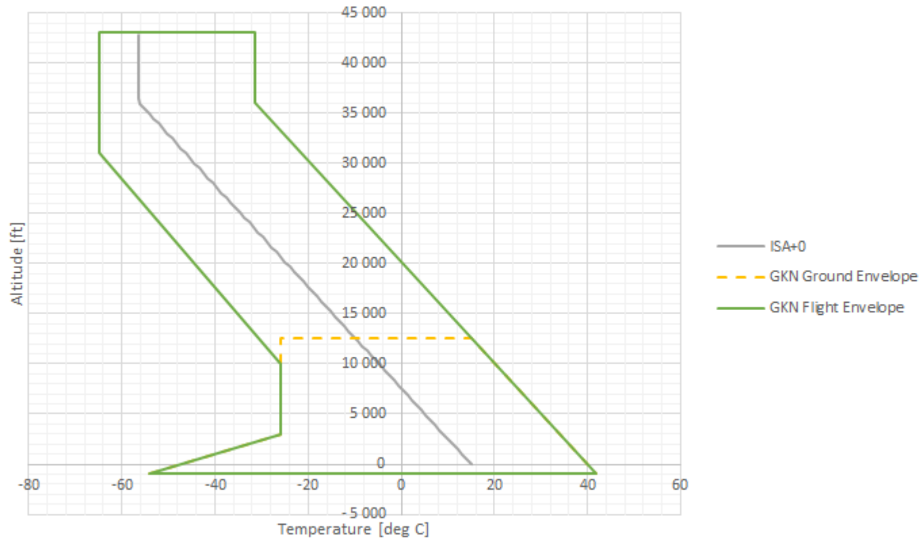

Figure 4 - Assumed operational temperature envelope

2.4 The Cryogenic System

As an anticipated means of compliance with CS25, the cryogenic hydrogen is used to cool an inert helium loop that maintains the required low operating temperature of the power distribution, inverter and motor combination. The hydrogen:helium heat exchanger (HEX) both cools the helium to 25K and vaporises the hydrogen to a cold gaseous form. Further conditioning of the gaseous hydrogen is powered by waste heat from the stacks as part of an integrated thermal management system.

Cold helium gas is then transferred directly to the motor as that has the most significant impact on powertrain efficiency. From the motor, the helium passes to the motor drive in which the majority of the heat load is generated. The returning 'warm' helium is still sufficiently cold that it can significantly reduce the cable mass of the DC supplies from the network controller (bus bars) to the drive. Obviously all cryogenic hydrogen and helium components are vacuum encased to avoid any build up of frozen air components.

3. Comparison of Cryogenic and Conventional High Voltage Systems

A simplified configuration of a non-cryogenic high voltage power distribution system is shown in figure 5. FCSM represents fuel cell stack modules and PDC is a power distribution centre.

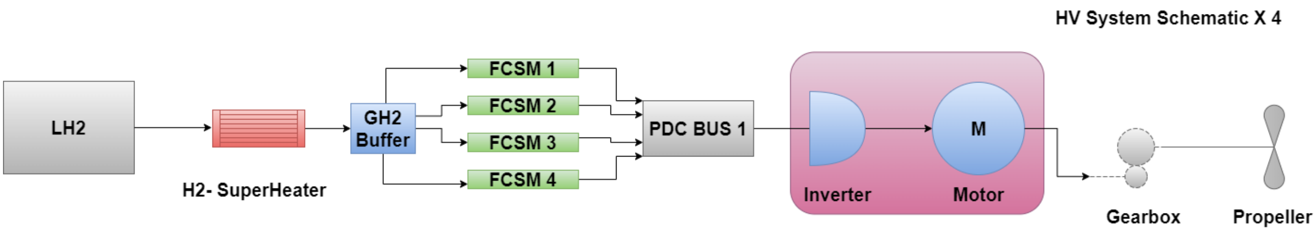

Figure 5 - Simplified non-cryogenic propulsion system

Both configurations have been applied to the same aircraft mission that represents the design range (1600NM) of the GKN-96 notional platform. Figure 6 shows the key power requirements of the mission for the 96 passenger aircraft.

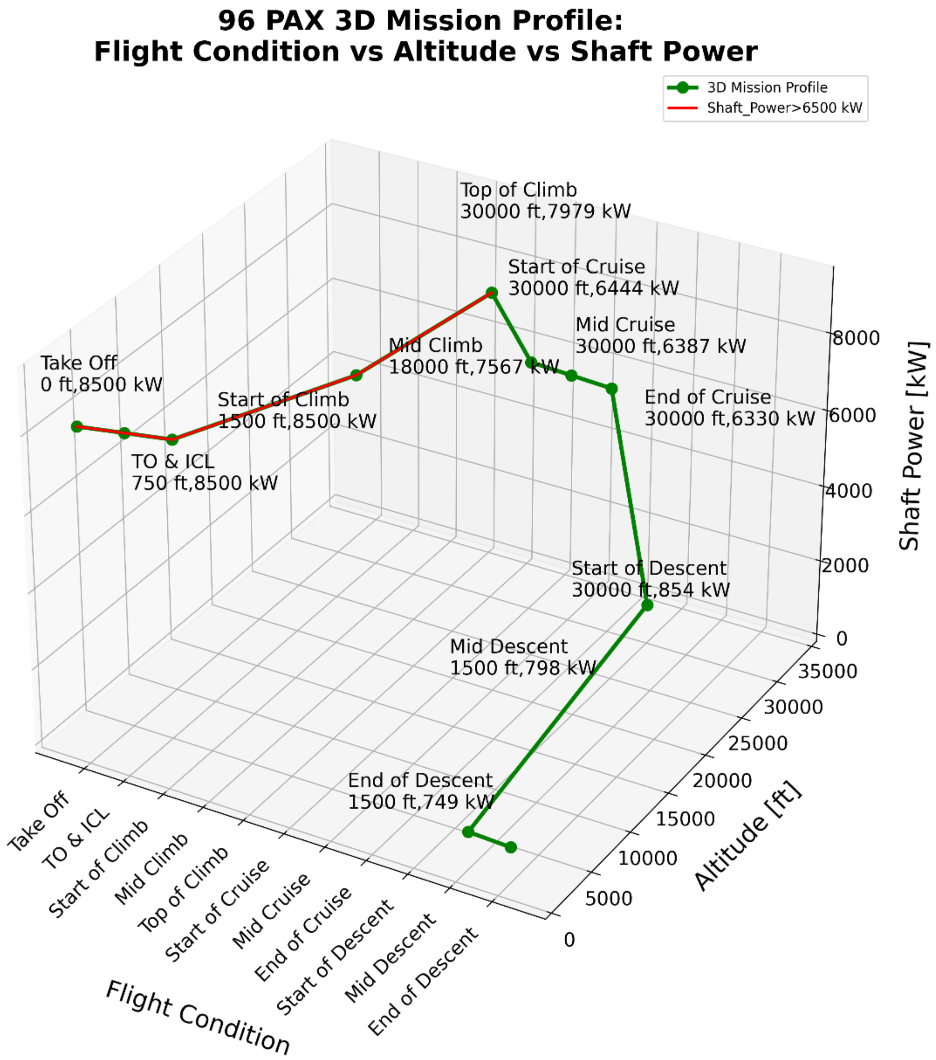

Figure 6 - Typical mission power profile

The data shown in figure 6 identifies typical power levels at selected waypoints of the mission. Note that the power levels shown are shaft power and may not fully represent the gross power output of the stacks.

3.1 Comparison of cryogenic and non-cryogenic systems for 48 and 96 pax aircraft

A comparison between cryogenic and non-cryogenic systems should consider two separate aspects; mass changes to major components (motor, inverter, etc.) and effects driven by improvements in the efficiency of the powertrain at cryogenic temperatures. As an example: if the overall cryogenic powertrain efficiency can be improved by ~10% then there will be a corresponding reduction in fuel burn and fuel system mass. This in turn will reduce the overall power generation requirement and reduce the fuel cell stack mass. Each of these have been captured in this analysis and the overall results are shown in figure 7.

The results for both the 48 and 96 passenger aircraft have been included in figure 7 and the results are very consistent. The direct impact on major components of improved powertrain efficiency broadly cancel out against the added mass of the cryogenic system. However, in both cases, the additional impact of reduced fuel burn for iso-range is significant and accounts for a reduction in mass of approximately 3% of the take-off mass. The mass penalty for the conventional power distribution system would require either a reduced range or a reduced payload.

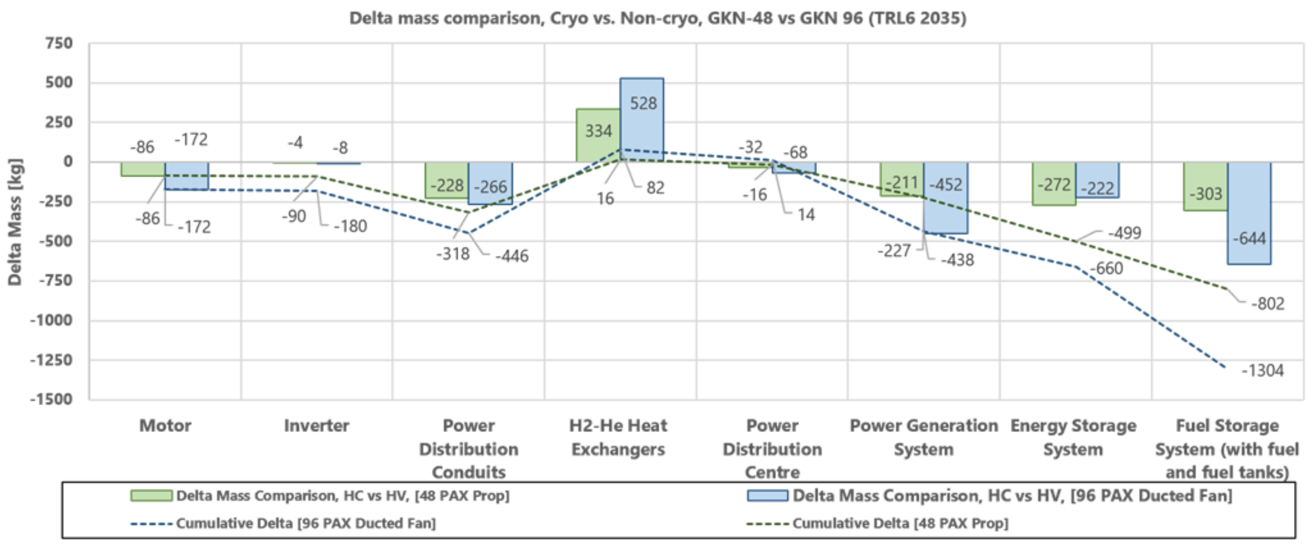

Figure 7 - Cryogenic system mass benefits analysis

The power distribution conduits account for the majority of the direct mass savings on the cryogenic distribution system. The cryogenic conduits include a helium conduit that houses the actual power cable and maintains temperatures below 75K. The helium conduit is contained within an outer vacuum pipe to ensure minimal heat addition to the helium. Calculations show that the conventional cable carrying the same power would weigh 4.6kg/m compared to the assembled cryogenic conduit at 2.7kg/m. For the GKN-96 aircraft the aggregate length of the distribution network exceeds 50m.

As noted in section 2.2, the voltage standard for the hyperconducting system in this analysis has been held constant at +/-270V. The non-cryogenic analysis has been completed for an increased level of +/-800V on the conventional system. The overall benefit accrued by the cryogenic system is dominated by the improved powertrain efficiency. Overall, the cryogenic powertrain has been previously shown [1] to be at least 10% more efficient at the peak power operating point.

4. Consideration of Centralized and De-Centralized systems

A quantitative comparison of centralised or de-centralised systems is due for completion in late 2024. At this stage therefore it is only possible to provide a qualitative assessment. Furthermore, the ongoing analysis will also assess implications for hydrogen combustion platforms.

Early indications are that there seems to be little advantage in terms of payload and range of converting to a combustion platform. This conclusion is based on; shared limitations on centralised fuel storage volume and the calculated powertrain efficiency benefits of cryogenic fuel cell systems. Initial concerns around the scalability of fuel cell based systems appears to have diminished as a result of the design iterations performed in H2GEAR including an ongoing investigation of a 160 passenger variant.

4.1 Lessons learnt from H2GEAR centralised analysis

The design iterations within H2GEAR have all generated ‘clean sheet’ designs made possible by the modelling environment GKN has created. This is in contrast to a number of other design studies that have assumed that a retrofit approach would be preferred. The shift to hydrogen fuel immediately changes the historical relationship between empty weight and MTOW in response to the increased power generation system fixed mass and the associated balance of plant (cathode air compressors, thermal management systems, coolant pumps, etc.), figure 8.

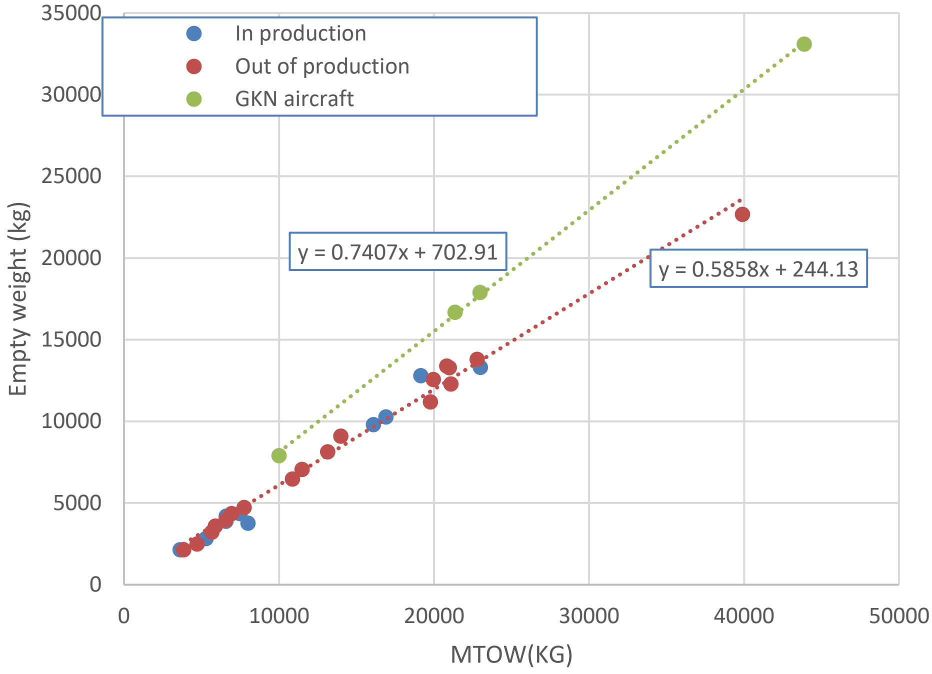

Figure 8 - Hydrogen fuel cell aircraft empty weight fraction

Not surprisingly this increase in MTOW compared to kerosene based platforms (15% - 20%) also increases the propulsive power requirement for hydrogen platforms. Some of that increase can be offset by efficient use of alternative energy storage systems and by changes in the manner in which the aircraft are operated.

It is important to note that, unlike conventional gas turbine units, the power generation system developed within H2GEAR does not evidence a power lapse rate with altitude. This is due to the controlled cathode air supply that ensures consistent performance regardless of ambient air pressure at any altitude. Fuel cells are a self-contained reaction that operate a relatively low temperatures compared to gas turbines and therefore their efficiency is not significantly influenced by ambient air temperature. In operation this absence of an altitude lapse rate can be exploited to reduce the overall installed power requirement by limiting the initial rate of climb at low altitude and compensating time to initial cruise altitude with the increased rate of climb capability at high altitude. The definition of the service ceiling becomes the design condition for the cathode air delivery pressure ratio and pressure of the hydrogen anode feed. There is scope to optimise the cathode and anode delivery systems to enable aircraft operations beyond 35,000ft altitude.

4.2 Definition of a de-centralised system

It is assumed that the definition of a centralised system is one in which power is distributed from a central power generation system (in this instance fuel cell stacks) to a number of remote power conversion nacelles. Those nacelles would only contain a motor and its associated electrical drive unit and could serve either a ducted fan or a propeller. The centralised system will be served by co-located air delivery, thermal management and power conditioning systems (balance of plant).

In contrast, a de-centralised system is one in which the energy source i.e. hydrogen, is stored in the fuselage and distributed, either as a gas or liquid, to remote nacelles. Each nacelle therefore must support all the necessary functions to process the hydrogen into useful electrical power i.e. fuel conditioning and fuel cells. Furthermore each nacelle is assumed to include a local balance of plant (cathode air supply, waste heat dissipation) and power conditioning.

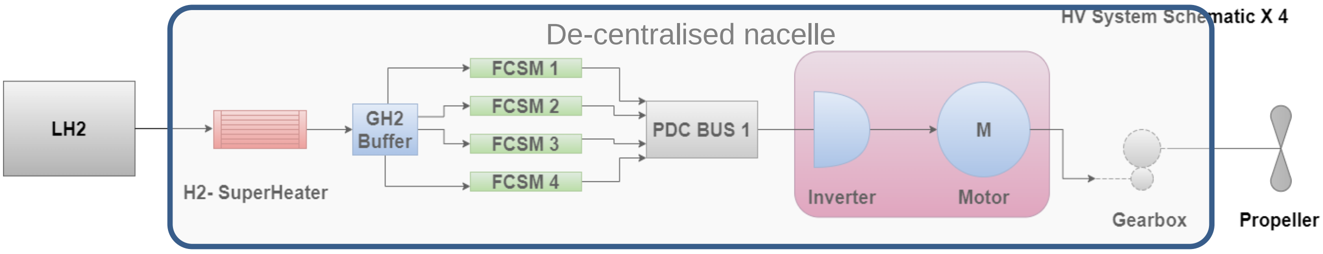

Figure 9 - Components of a de-centralised nacelle

Figure 9 illustrates the components to be integrated into a de-centralised nacelle assuming that liquid hydrogen is being distributed to the nacelle.

- The Superheater warms the hydrogen to >300K prior to entering the fuel cells.
- The GH2 buffer provides a transient capability for rapid changes in flow demand.
- The Fuel Cell Stack Modules (FCSM) receive both hydrogen and air to deliver electrical power.
- The power distribution centre (PDC) conditions the DC power prior to distribution to the inverter and motor.
- The cathode air supply is not shown in this figure but will require a compressor in order for the fuel cells to continue to operate at altitude.

To clarify the differences between these centralised:de-centralised approaches and in the absence of a detail design study, it is proposed to consider just two simple aspects:

1) Is the concept scalable to larger platforms?
2) Is the concept safe and compliant with anticipated future standards for hydrogen aircraft?

4.1 Scalability

The H2GEAR team have shown that hydrogen fuel cell aircraft concepts appear viable at least to 100 passengers and 1600NM range. More recent design iterations have also shown that extensions in payload up to 160 passengers, also at 1600NM range, are possible. This latest embodiment has been constrained to operate from a standard single aisle ‘C’ gate. It is concluded that at least for a 2050 time frame targeting the single aisle market, that a zero emission, cryogenic, hydrogen fuel cell propulsion system is scalable. The assumption within H2GEAR of using a 3+3 seat arrangement for both 48 and 96 passenger aircraft is important in making the system practical and scalable.

Several embodiments of a de-centralised approach have been proposed e.g. Airbus Zeroe and Universal Hydrogen. They share the concept of a series of nacelles, each fed by a form of hydrogen and functionally self-contained.

An aircraft of similar scale and performance to an ATR-72-600 [4] will require an aggregate of ~4.0MW of installed shaft power at the original take-off weight. As a twin, each nacelle would need to produce more than 2.0MW when secondary loads are included. If the increase in take-off weight for hydrogen aircraft, as shown in figure 8, is accounted then the aggregate installed power would increase beyond 2.3MW per nacelle. This will require an increase fuel cell stack count and increased balance of plant etc..

While additional nacelles may appear to ease the second segment climb constraint (3% for a 4 engine aircraft with OEI) it is likely that only minor reductions in overall power would be achieved. If too much emphasis is placed on climb performance it is anticipated that the aircraft will be limited in cruise altitude and speed depending on how the cathode air delivery system is configured.

Continuing with the ATR-72 concept in a twin nacelle configuration, to produce the required power level will need approximately 10 IT-PEM stacks assuming a technology standard expected to be available in 2030. Without considering the integration of the thermal management, cathode air delivery and supporting energy storage system, a conceptual nacelle will already occupy a significant fraction of the propeller disc area.

If installed power requirements increase linearly with payload at iso-range then it is likely that de-centralised systems will become increasingly inefficient as the nacelle size increases. Increasing the number of nacelles is a potential mitigation but this will also increase component count and nacelle drag, amongst many other factors. A de-centralised 100 passenger aircraft may only be achievable with 4 or more nacelles and as a consequence may be limited in cruise altitude and/or speed. It is considered unlikely that a de-centralised system would be appropriate as a single aisle aircraft replacement and may be limited to regional missions.

4.2 Safety

It is not proposed to explore the relative performance of a de-centralised approach in this paper. There is value however in identifying some of the functional challenges associated with a de-centralised approach.

4.2.1 Operation with One Engine Inoperative (OEI)

The propulsion system of a conventional kerosene twin propulsor aircraft is often sized by being compliant with second segment climb gradients in the event of OEI. It would appear that a twin de-centralised system would be similarly constrained. By contrast, a centralised system with a multi-channel electrical network can not only meet the OEI standard but could also provide additional power to the remaining propulsors thereby relaxing other aspects of the aircraft design. The impact of increased sizing cases for conduits etc. appears to be acceptable and achievable from design iterations completed with H2GEAR.

4.2.2 Integration

The integration of this variety of components and systems into a nacelle will create a very densely packed environment that requires consideration by Particular Risk Analysis (PRA) and Zonal Safety Analysis (ZSA). Within the nacelle there are likely to be hydrogen feeds, high power cables, compressors and cathode air delivery pipes. Damage to any of those systems could result in either partial or total loss of power from that nacelle.

A PRA for uncontained rotor failure of the cathode air compressor could result in a hazardous situation according to the usual risk assessment ratings. The presence of hydrogen in the zone could further increase that risk to catastrophic. Therefore careful placement of the compressor/turbine planes would be required to avoid sensitive components. These in turn could increase the gross volume and mass of the nacelle. Equally a ZSA would need to be performed for example, to assess the risks associated with hydrogen leakage in a closed volume.

For a centralised system it is possible to isolate sensitive components and hydrogen paths away from turbomachinery and other blade release trajectories.

The distribution of hydrogen through the aircraft would also necessitate the need for vent paths to be created in any zone in which pooling of leaked hydrogen could occur. Within the wing box for example, there would be a need for a continuous air refresh similar to that required for existing kerosene tank boundaries. However, with the significantly reduced flammability limit of hydrogen (<4% by volume) compared to kerosene, the air flow rates to maintain concentrations below acceptable levels will be many times that of conventional fuel boundaries. If liquid hydrogen is to be distributed then additional protection may be required to avoid the leakage of any cryogenic liquid contacting airframe components either metallic or carbon based.

5. Conclusions

The H2GEAR team have developed an advanced understanding of the potential benefits of a cryogenic H2EP system. Any development of a hydrogen fuelled aircraft must be undertaken in the environment of a notional aircraft platform. The key considerations of safety and certification should be included as early as possible and the aircraft should not be assessed purely on performance trades.

Analysis presented in this paper showed an overall benefit in terms of aircraft level mass for a hyperconducting propulsion system when compared against a conventional high voltage system. Those benefits have been shown to be approximately 3% of the MTOW for both aircraft considered. Given that that percentage of the MTOW is approximately the same as the amount of hydrogen fuel for each mission, the impact should be seen as significant. The mass benefit could be used to either increase range or payload but the former is likely to be constrained by the volume available for fuel storage in the rear fuselage. The inclusion of a cryogenic system is broadly mass neutral at a component level but significant benefits accrue from the improved efficiency of the powertrain.

A de-centralised system presents a different set of challenges during a preliminary design phase. Increased priority should be given to PRA and ZSA and the impact of increasing nacelle size for increased payloads may negatively impact the flight envelope. All de-centralised concepts will be dependent on the distribution of hydrogen either gaseous or liquid. It remains to be proven that this is acceptable within a certification framework.

6. Acknowledgements

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8. Copyright Statement

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